Toward the Green City: Biodigesters as a Catalyst for a New Urban Form

Carl S. Sterner and Lyle Solla-Yates

Physical infrastructure -- rail, airports, bridges, sewers, and waste treatment -- shapes the flows and form of the city. Both form and flows are central to the sustainability debate, and to the concept of the Green City. This paper utilizes the concept of "urban metabolism" -- a field that studies the flows of nutrients through a city -- to better understand the mechanisms by which infrastructure shapes the city, and to assess the impacts of infrastructure decisions. This offers a method to evaluate infrastructure based upon desired outcomes -- for example, which infrastructure options will promote re-use of nutrients?

In the past, major changes in physical infrastructure had significant impacts on the metabolism and the form of cities. We briefly consider three case studies: paved roads, sewer systems, and the regional transportation technology introduced in the late nineteenth through mid-twentieth centuries. We argue that in each case, new infrastructure construction shifted metabolic flows and consequently re-shaped the city. In light of this historic view, this paper looks at the impacts of anaerobic biodigestion as a new waste management system, and evaluates its potential to achieve Green City goals.

This paper considers the flow of four critical nutrients: carbon, nitrogen, water, and money. We specifically extend the metabolic approach to include the flow of currency because of its importance in determining the ultimate success of infrastructure.[1] We examine these nutrients in the context of the "extended urban food system," which includes farms, fertilizer, food service and consumption, and disposal of resulting organic waste.

The Green City

The Green City is an urban settlement in which development improves rather than harms the environment.[2] First, ecosystem services -- the "free" services provided by a healthy ecosystem -- are valued, protected, and enhanced. Some of the critical ecosystem services considered here are water storage and infiltration, carbon sequestration, and the creation of habitat, which provides wildlife, pollination, and temperature regulation, among other things.[3] A Green City preserves these resources, as well as the processes that create and maintain them. The second defining characteristic of a Green City is a cyclical or biomimetic metabolism that mimics the cyclical flows of nutrients in a natural ecosystem, creating outputs that can be reused in other biological systems (Fig. 1).[4,5,6] These two features are interrelated: metabolic flows can either support or degrade an ecosystem's capacity to provide services.[7]

Some of the tools typically used to achieve these design goals are regional planning based upon landscape ecology, which focuses on elements such as wildlife corridors; low impact development (LID) strategies, which focus on stormwater management and infiltration; an increase in urban greenery (street trees, parks, and natural areas for both recreation and habitat); a strategy of emphasizing native plants; and creating a closer link between the city and its food production. However, absent a larger frame of reference or method for evaluation, these small-scale interventions may not produce the desired outcomes at the city scale. Better methodologies are needed to understand and quantify the impacts of proposed actions -- including infrastructure -- on the city.

The Contemporary City

In contrast to the Green City, the metabolism of the contemporary city is conceptually linear: cities transform resources to waste, simultaneously depleting natural capital and overwhelming natural capacity to recycle nutrients.[8] The draw-down of resources and buildup of waste are unsustainable; and the contemporary urban system has created myriad environmental problems in its relatively brief existence. Three biological nutrients are critical to understanding the modern problems of environment and city form: carbon,

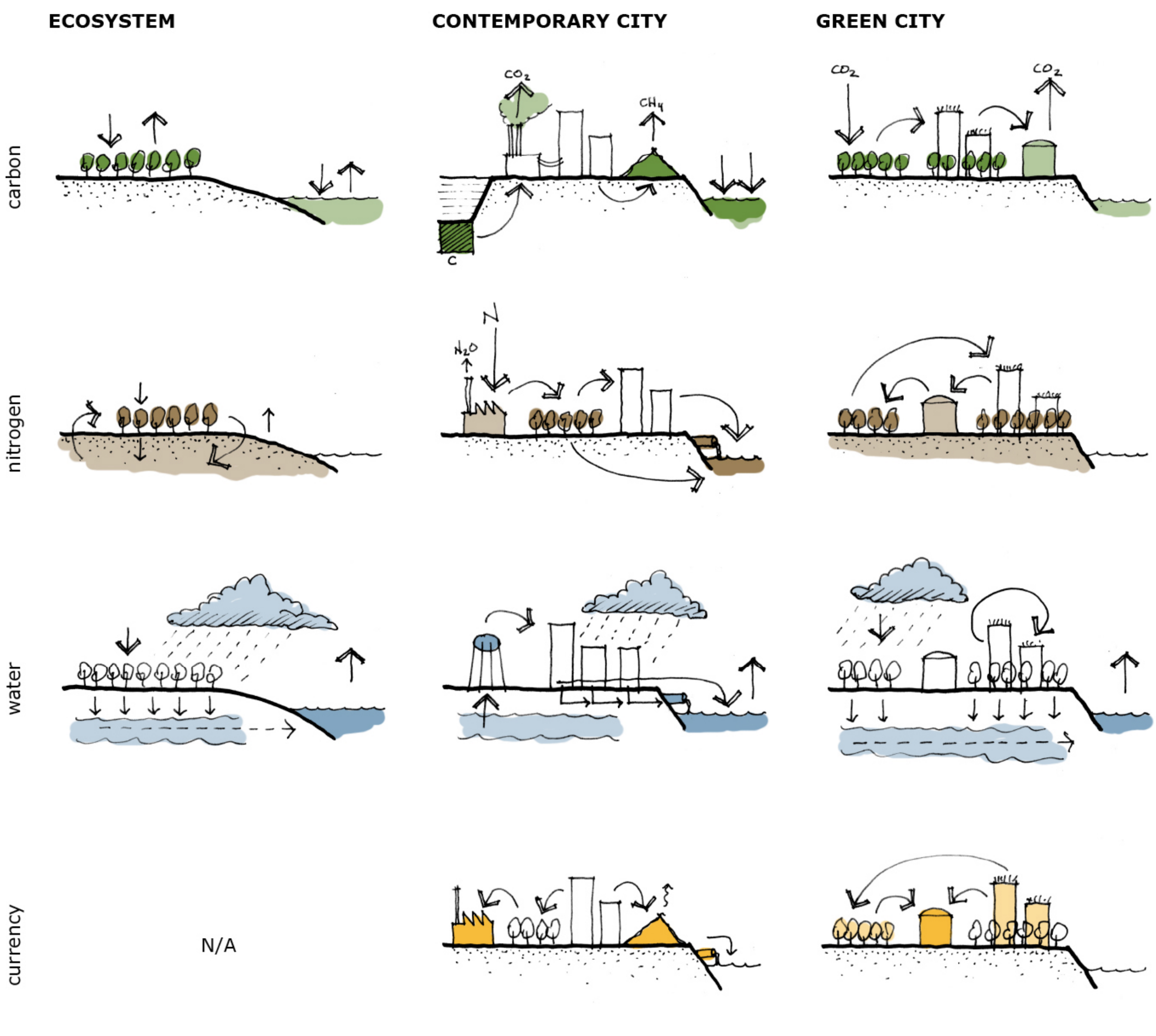

Fig. 1. Conceptual flows of carbon, nitrogen, water, and currency through an ecosystem, the contemporary city, and the green city.

nitrogen, and water. These nutrients flow through an extended food system comprised of agricultural production, distribution, consumption, and disposal of organic waste. Viewed at the macro scale, this system takes these nutrients from their natural disposition in the ecosystem to places where they cause ecological harm (Fig. 1). In addition, this paper expands the metabolic model to consider the flow of currency through the extended food system. Understanding the flow of this "economic nutrient" is often critical to understanding the success or failure of a given system.

Carbon

Current extended food systems extract carbon from underground and concentrate it in the atmosphere, changing the climate and acidifying the oceans. The extraction and burning of fossil fuels for farm equipment, food distribution, and fertilizer production essentially moves large amounts of carbon (in the form of oil and natural gas) from underground reservoirs into the atmosphere. While crops absorb carbon from the atmosphere, it is often less than the native ecosystems they replaced.[9] Oceans absorb about one third of the additional atmospheric carbon. This increases ocean acidity, with potentially severe consequences for marine ecosystems and fisheries.[10] Traditional forms of organic waste management -- landfills and conventional sewage treatment facilities -- convert much of the embedded carbon to methane (CH_4), which has 25 times the global warming potential of carbon dioxide.[11]

Nitrogen

Current extended urban food systems extract nitrogen from the air and the soil and concentrate it (a) in waterways, which harms aquatic life, and (b) in the atmosphere in forms that contribute to climate change. Industrial agriculture rapidly draws down soil nutrients, including nitrogen.[12] This nitrogen is replaced with artificial fertilizers, which are produced largely with nitrogen extracted from the atmosphere, and with methane from natural gas. This process produces nitrous oxide (N_2O) as a byproduct -- a potent greenhouse gas 310 times more effective at trapping heat than carbon dioxide.[13] Once applied to the land as fertilizer, much of the nitrogen runs off of fields into water bodies where it causes eutrophication and harms aquatic life. Agricultural runoff from Midwestern states has created a large "dead zone" in the Gulf of Mexico at the mouth of the Mississippi River.[14] The nitrogen absorbed by food crops travels to cities where it is consumed and deposited in sewers. Waste treatment plants either flush the nitrogen into waterways, where it contributes to aquatic degradation, or release it to the atmosphere as nitrous oxide where it contributes to climate change.[15]

Water

Current extended urban food systems drain groundwater for irrigation and consumption, and convey rainwater into bodies of water in ways that cause soil erosion and harm biodiversity.[16] Extensive water consumption can create fresh water scarcity, most notably in arid climates and coastal communities that suffer from salt water intrusion such as in New York, California, and Florida. In cities, water drawn from aquifers is used and then conveyed to sewers, where it is combined with organic waste and often street runoff that contains heavy metals, salts, debris, and chemical pollutants. Many of these contaminants are not removed by traditional waste treatment processes before the water is release to waterways.[17]

Currency

Finally, current extended food systems include payments by farmers to external parties for fertilizer and fuel, payments by consumers for food, and payments by distributors and consumers for waste disposal. Costs are also

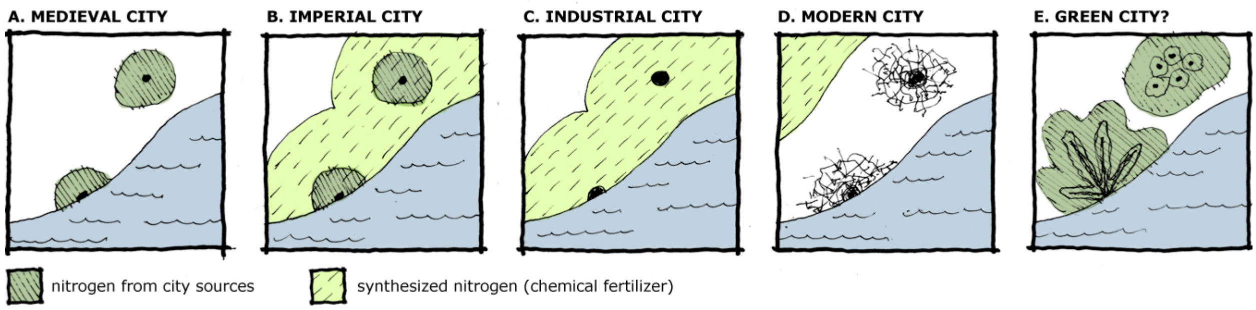

Fig. 2. The changing form of the city in relationship to flows of nitrogen between city and farmland. In the medieval city (A), nitrogen from the city made the area immediately beyond the city most valuable for farming. Nitrogen imported from colonies increased the availability of nitrogen in the imperial city (B). Shifts in infrastructure and policy ended the reuse of urban nitrogen, and the industrial city (C) expanded into its former hinterlands. In the contemporary city (D), transportation infrastructure has allowed vast separation of city and agricultural production, and has contributed to urban sprawl. The Green City (E) may adopt a polycentric or decentralized urban morphology, as the city's nitrogen flows are reconnected to agriculture.

incurred by the damage created by current fertilization and disposal methods. The high costs of the current system lead many governments to subsidize commodity crops less likely to spoil. This makes some kinds of food affordable, but may contribute to human health problems such as the obesity epidemic.[18]

These elements of the urban metabolism -- fuel, food, water, and currency -- have combined to shape the contemporary city. Pre-industrial cities were generally characterized by dependence on renewable, local, and secure sources of carbon, water, and nitrogen. Infrastructure projects shifted this metabolism over time to create the present-day system.

The Development of the Contemporary City

Major infrastructure interventions have helped to create the metabolic problems of the modern city (Fig. 2). Physical infrastructure helps to shape the metabolic flows, which in turn help to shape city form. We consider three case studies that had significant impact on urban metabolic flows: paved streets, sanitary sewers, and regional transportation networks. This analysis extends the traditional metabolic model in three ways: first, as discussed above, it includes monetary flows in addition to the typical nutrient flows; second, it focuses on the impacts of specific infrastructure decisions on the metabolism of the city; and third, it considers the impacts of these metabolic changes on city morphology.

Paved Streets and the Flow of Water

In the medieval city, household wastes were almost entirely organic. These wastes were deposited onto unpaved streets where they were consumed by pigs and other livestock or mixed with mud and manure.[19] As population grew and cities expanded, this strategy created a health hazard and a nuisance to transportation.[20] Paris and London began paving their streets as a public health measure as early as 1292, when King Phillip Augustus decreed that all Parisian streets be paved; however, it was not until the second half of the eighteenth century that street paving was implemented in earnest.[21] It was believed that paving streets would allow street sludge to wash away, leaving the city clean and healthy, without the miasma -- foul air -- that was believed to cause disease.[22]

Over time, increasingly impervious street construction and increases in the quantity of paved surfaces shifted the flow of water in the city. This created a number of new problems. Rainwater and household water could no longer infiltrate into urban land; as a result, stormwater often flooded basements and caused cesspits to overflow.[23] Cities began to construct drainage ditches to manage stormwater flow, some of which were covered to manage the stench. These early modern sewers began to appear in Paris and London in the 14th century.[24] However, sanitary conditions continued to deteriorate. By the mid-nineteenth century cesspit failure had grown so acute that it proved to be a major force in the adoption of sanitary sewers in cities such as Paris and London.

While paved streets ultimately did little to improve public health, they proved a benefit for trade. By making transportation easier and reducing the costs of bringing goods to market, they stimulated urban growth and the spatial reach of the city.[25]

Sanitary Sewers and the Flow of Nitrogen

Between the fifteen and nineteenth centuries, increasing population, deepening soil depletion, and cold weather created food scarcity throughout Europe.[26] This led to increasing demand for fertilizer.[27,28] Cesspits -- covered tanks for storing sewage -- became a primary means for managing urban waste.[29] Waste collected in cesspits was emptied out by "night soil collectors," and was then processed and sold at a profit to area farmers for use as fertilizer.[30] This system made proximity to urban centers advantageous to farmers, allowing easy access to the marketplace and to a vital source of fertilizer.

In the 1850s, Paris and London initiated major sewer construction efforts. Both cities arrived at the same system for different reasons -- a sanitary sewer that evacuated organic wastes, stormwater, and household water into local waterways.

In London, public health was threatened by cesspit failure, which caused contaminated water to flow into public wells. These failures resulted from two major forces: the new availability of less expensive fertilizer imported from South America beginning in the early nineteenth century,[31] and the spreading installations of water closets. The new competition from imports made night-soil less profitable, while water closets generated more waste water than cesspits could handle, creating offensive and dangerous overflows. In addition, water closets diluted organic waste, increasing the difficulty of manufacturing fertilizer from night soil.[32] The growing popularity of water closets and inexpensive fertilizer collaborated to create failures in the cesspit system. British engineers built a combined sewer, with unsuccessful plans to re-use the diluted sewer water in agriculture.[33]

In Paris, the desire for a clean, hygienic city provided the primary motivation for the construction of two pieces of infrastructure: a public water system that provided water for household use and street cleaning, and a sewer system for stormwater and street cleaning. Paris, like London, suffered from problems with the cesspit system; however, regulating and upgrading this system to protect public health was seen as an entirely separate project. Major figures including the planner Georges-Eugène Haussmann objected to using sewers for waste, fearing such a system would eliminate a vital source of fertilizer. Many political actors supported the existing waste management system: the city generated revenue from "night soil" fertilizer; the night-soil collectors defended their livelihoods, and health advocates worried that human waste in waterways would harm water quality and public health.[34]

Despite the consensus for the continued reuse of waste in both Paris and London, both cities fundamentally changed their urban metabolisms within a very short period. In Paris, the introduction of sewers created unintended economic consequences that ultimately undermined the cyclical metabolism. Free public water and the increasing popularity of water closets led to rapid increases in residential water use. As in London, cesspits were not equipped to handle these flows, and overflowed frequently. In London, this forced the construction of the combined sewer, but in Paris the result was a growing demand for connection to a sewer that was not intended for waste. In 1852, in an effort to alleviate cesspit overflows, Paris mandated sewer connections for household water, but specifically prohibited water from latrines. But this position was untenable: by 1884, the connection of privies to the sewer was legalized, and a decade later, in 1894, it was made mandatory.[35] This critical grassroots-led change occurred in part because the key decision-makers -- individual tenants -- did not directly benefit from the reuse of waste, and were not harmed economically by the loss of fertilizer. In addition, they did not pay directly for sewer and water connections -- these were paid for by landlords and largely subsidized by the city.[36] The decisions of those tenants were in this sense economically rational, despite the political consensus for re-use.

The cumulative effect of sewers was to disconnect agricultural productivity from the output of cities. The system redirected the nitrogen-rich waste that previously flowed to farms into local waterways. In the process it wiped out the nightsoil collectors, who provided the metabolic link between city and country. Farms and cities, no longer interdependent, became spatially segregated. Any land with access to fertilizer (imported or chemical) became an equivalent commodity. The land directly adjacent to the city, no longer seen as most valuable for farming, was swallowed up as urban populations grew. At the same time, the city continued to grow in density as more people found themselves able to live safely near each other because of improved sanitation. Prior to the sanitary sewer, the city was stratified vertically by income, with top floor apartments prized by the wealthy, away from the grime and miasma of the street. The advent of sewers correlates with increasing horizontal social stratification. The new class of industrial workers spread out from the city center to surrounding slums not connected to the sewer, in the process creating the first suburbs.

Regional Transportation Networks and the Flow of Carbon

Transportation infrastructure -- namely rail and interstate highways -- had additional impacts upon metabolism and city form. They extended the resource base of cities, creating what Herbert Girardet calls the "global hinterland."[37] Resources are brought into the city from increasingly vast distances, and wastes are shipped literally around the world. This expansion was powered by the energy density inherent in fossil energies, and the extensive use of fossil fuels shifted the carbon metabolism of cities. Transportation networks also accelerated the problematic nitrogen and water flows already established by earlier systems. Fossil fuels expanded industrial agriculture and deepened society's reliance on chemical nitrogen, now sourced from the atmosphere.

The impact of transportation networks on city form is well-documented elsewhere.[38] Modern sprawl -- relatively undifferentiated geographic expansion largely devoid of green space or habitat –- emerges from the creation of regional transportation networks, and from interstate highways in particular. This development was subsidized not only by heavy government investments in transportation projects, but also by continued government financing of public sewer and water systems in new (and increasingly distant) locales.

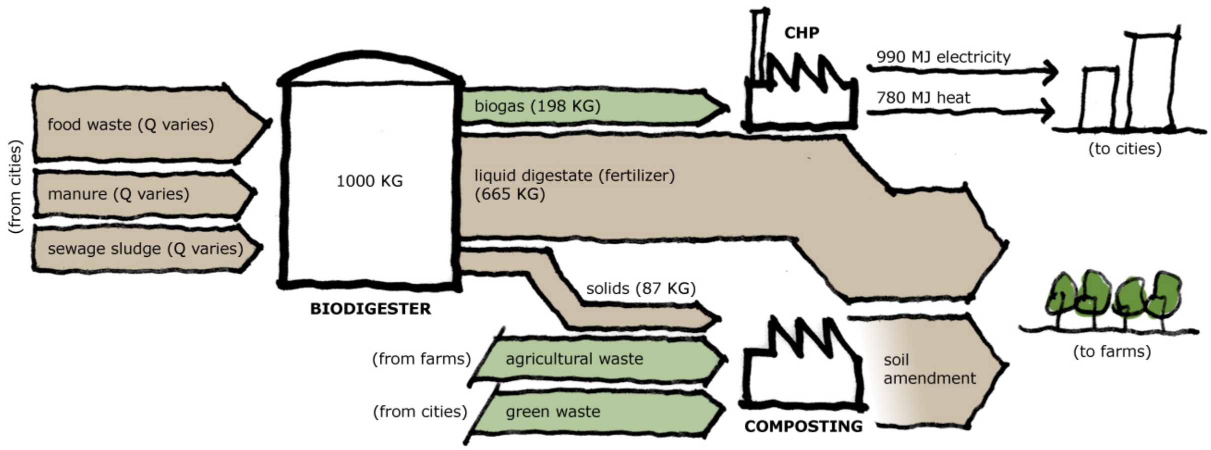

Fig. 3. Inputs to and outputs from an anaerobic biodigestion system that includes a combined heat and power (CHP) plant and a composting facility. Size of arrows represents approximate mass in kilograms, based upon 1000 kg of inputs to the biodigester. Data from Bohn, et al., "Food Waste Disposal," and the Renewable Energy Association, "Anaerobic Biodigestion Energy Balance," http://www.r-e-a.net/biofuels/biogas/anaerobic-digestion/ad-energy-balance (accessed September 13 2010).

In addition, the expansion of suburban development corresponds with dramatic increases in per capita water consumption, largely for landscaping uses. Suburban lawns also become an additional source of nitrogen pollution.

The problems created by these infrastructure decisions require new approaches. Infrastructure decisions made today must be considered in a broader ecological context in order to avoid the unintended consequences that characterized the historical investments discussed above.

Biodigesters and Urban Metabolism

As old waste management strategies become unworkable -- due to regulation of combined sewer overflows, increasing costs of landfilling, limits on greenhouse gas emissions, and increasing awareness of environmental costs -- municipalities are exploring a number of alternatives. One alternative that is becoming increasingly popular worldwide is the use of anaerobic biodigesters to treat organic wastes. We utilize the metabolic framework to consider the potential impact of this new system on urban metabolic flows, as well as the form of the city.

Anaerobic biodigesters are sealed containers that break down organic matter in an oxygen-free environment, producing methane-laden biogas and nutrient-rich biosolids (Fig. 3). They can accept a wide variety of organic wastes -- from food wastes and sewage sludge to agricultural waste and manure. The type and quality of inputs affects the outputs: food wastes, for example, have a high energy content and are therefore valuable for biogas production;[39] food wastes are also able to produce high-quality soil amendments because of their low contamination.[40]

Biodigesters are not a new technology: they are commonly used in municipal wastewater treatment plants to reduce and stabilize sewage sludge, and household-scale units have been used for decades in rural China and India to produce biogas.[41] They are also currently used in dairy farms and pig farms, cost effectively meeting clean water requirements while producing clean energy and fertilizer. Recently, U.S. interest in biodigesters has grown -- particularly in expanding the use of biodigesters to process food and other municipal organic waste. In California, several municipal biodigester facilities have been built, including the East Bay Municipal Utility District facility in Oakland and the Chevron-Millbrae facility in Millbrae, and more are proposed.[42] These investments are largely spurred by a 1989 California law requiring municipalities to divert 50% of their waste stream from landfills by 2000, and by state laws and incentives aimed at reducing greenhouse gas emissions.[43]

For the purposes of this analysis, we focus specifically on a wet biodigestion system run in combination with a composting facility and combined heat and power (CHP) plant (Fig. 3). The composting facility treats residual solids from the biodigester to produce high-quality soil amendment. The CHP facility burns biogas to produce heat and electricity. Part of this energy is used to run the biodigestion facility; the rest can be sold back to the grid. While other types of biodigestion facilities exist, this design is used because (1) it is effective at treating urban wastes (including food and sewage); (2) the addition of CHP and composting facilities produces valuable end products; and, as a result, (3) recent built and proposed biodigestion facilities tend to favor this design. Hereinafter, this system is referred to collectively as the "biodigestion system."

While most biodigester projects to date have been appended to existing systems or viewed as a one-off solution, when viewed as a primary waste management in their own right it becomes apparent that biodigesters have the potential to dramatically shift the flows of resources through a city. Specifically, an extended urban food system dominated by biodigesters would close metabolic loops, helping to recreate the flows of nitrogen and carbon that characterize natural systems.

Nitrogen

Food crops pull nitrogen from the soil and atmosphere; biodigestion systems capture the organic waste that emerge from food production, distribution, and consumption, treat the waste, and return the nitrogen to the land in the form of fertilizer and soil amendments. In doing so, it supplants some of the need for synthetic fertilizers at the same time that it avoids the liabilities associated with releasing nitrogen to waterways or into the atmosphere.

Carbon

Food crops pull carbon from the air; bio-digestion systems capture carbon from organic waste crated during production, distribution, and consumption, convert it to methane, burn the methane for energy, and return the carbon to the atmosphere in the form of carbon dioxide. Thus the system maintains a neutral carbon balance. Because the biodigestion system displaces some need for synthetic fertilizers, it also displaces the fossil-fuel based carbon emissions associated with fertilizer production. In addition, carbon that would have otherwise been released to the atmosphere in the form of methane from landfills is captured and burned for energy, potentially displacing dirtier sources of energy.[44] A recent study of a proposed biodigestion system in Humboldt County, California, projected that the system would offset nearly five megatons CO^2-equivalent per ton of waste digested.[45]

Water

Biodigestion systems do not directly affect the flow of water through the extended urban food system; however, the system may have indirect impacts on the flow of water. These indirect impacts are discussed below.

Currency

As flows of carbon and nitrogen are captured, quantified, and monetized, they can become associated with flows of revenue. These flows potentially put waste treatment in a much stronger financial position, and its role shifts from being primarily a manager of liability to being primarily a producer of goods. Facilities are paid for their service of waste treatment as well as for their products (fertilizer and energy). Both "recycled" compost and renewable energy have the potential to command premium prices, further improving the economic prospects of biodigestion systems.[46]

The economics of biodigestion systems are generally favorable. A lifecycle cost assessment completed for the proposed Humboldt system found the system to be less expensive than either municipal composting or traditional landfilling -- even without considering potential revenue from sales of fertilizer, soil amendments, or carbon offset credits.[47] For-profit waste management companies have emerged in both the U.S. and in Europe, borne of the realization that the end products (particularly fertilizer) of "waste treatment" can be at least as valuable as the service provided.[48] This association between organic waste and potential revenue creates an economic incentive for the increased use of waste.

Shaping the City

The shifts in metabolic flow discussed above create a series of indirect impacts on the city. We look at four of the indirect mechanisms, or "forces," that have the potential to reshape the city (Table 1). We argue that these forces are supportive of the Green City goals outlined above, and could be leveraged or augmented to create further incentives for particular Green City measures. While these forces are speculative and require further investigation, they are also potentially the most significant effects of this new infrastructure.

Force 1: Waste Diversion

The link between waste and profit creates an economic incentive for increased diversion of organic waste. The impact of this shift should not be understated. In the same way that the economics of nineteenth century Paris served to undo the cyclical metabolism, reconnecting

Table 1. Forces that shape the city.

Force	Primary Nutrients	Description	Effect
Waste diversion	Currency	The link between waste and profit creates an incentive for increased diversion of organic waste.	Restores cyclical metabolism.
Metabolic balance	Carbon	Biodigesters create a pull for high carbon waste.	Supports urban greenery, including parks & agriculture.
High quality inputs	Water & non-nutrients	Optimizing quality & profitability of fertilizer means minimizing contaminants and the dilution of waste in water.	Provides motivation for (a) Low Impact Development, and (b) green chemistry / reducing toxicity.
Linking city and farmland	Nitrogen & currency	The exchange of nitrogen creates an economic and metabolic link between city and country.	Potential to changes urban morphology.

profit to the reuse of waste creates an economic "engine" that has the potential to again shift metabolic flows, reconnecting the two ends of the extended food system.

Private waste management companies will likely compete with municipalities for the optimal waste streams -- particularly food waste. Farmers and distributors could gain an additional revenue stream by selling wastes that were previously liabilities. This could potentially lower food costs for the entire area.

In practical terms, this force will likely be manifest in cities as new systems of waste collection that are focused on capturing useful nutrients and separating waste into its constituent streams. This separation is also a critical issue. In *Cradle to Cradle*, William McDonough and Michael Braungart conceive of two "metabolisms": the biological metabolism, consisting of organic wastes that must be nontoxic and biodegradable; and the technical metabolism, consisting of material that can be recycled or reused.[49] Disentangling these metabolisms is critical for the effective reuse of nutrients; and biodigestion systems create an economic motivation to do precisely this.

Force 2: Metabolic Balance

A biodigestion system creates a demand for a balanced carbon and nitrogen metabolism at the urban scale. Biodigesters operate best with inputs that have a carbon to nitrogen (C:N) ratio between 25:1 and 30:1 by mass.[50] City wastes (sewage sludge and food wastes) are relatively high in nitrogen (around 10:1),[51,52] and therefore benefit from dependable carbon-rich sources like green wastes and agricultural wastes to balance them. Composting residual solids with high carbon wastes produces a better soil amendment. This demand for high carbon waste reduces the disposal costs of farming, landscaping, and forestry.

A number of Green City measures rely on literally increasing greenery within cities, whether through riparian corridors and habitat patches that provide habitat and improve water quality, street trees and parks that sequester carbon and mitigate urban heat island effects, or green roofs and bioswales that treat stormwater. Reducing disposal costs for green waste improves overall cost effectiveness of these uses to some extent. In this way, biodigesters create a supportive context for a number of other Green City measures, and create opportunities for potential mutually beneficial relationships.

Force 3: High Quality Inputs

In order to produce quality fertilizer, it is necessary to control the quality of what is going into the biodigester. This is especially important for sewage sludge, where heavy metals, pharmaceuticals and solvents can endanger health.[53] It is preferable to prevent these pollutants from entering the biodigestion system, but there may also be treatment and separation options. Biodigesters will serve to draw attention to this issue by tying the quality of the waste stream more closely to the economic performance of waste treatment.

In addition to contamination of sewage, excessive dilution of organic waste in water is a challenge. Again, treatment and separation options exist, but can be costly -- it is less expensive and more efficient to separate these flows initially. This creates a pull for Low Impact Development strategies to intercept runoff water, as well as water conservation measures and sewer maintenance. Water reduction measures include reuse of graywater, including for industrial, agricultural, and landscaping uses.

While the potential economic value of sewage sludge is likely not sufficient to justify large-scale shifts in water use or contaminants, a system based upon reuse of waste draws attention to these issues, and is supportive of efforts to minimize ecological toxicity, reuse water, and improve stormwater infiltration.

Such a system also creates an economic constituency whose interests are aligned with reuse -- the modern-day equivalent of the night-soil industry.

Force 4: Linking City and Farmland

Re-establishing the flow of nutrients between the city and its hinterland tightens economic relationships between the two, potentially acting to improve farming profitability and bring agriculture closer to the city and even into the city.

As the cyclical metabolism takes hold, the edge of the city becomes a valuable membrane where exchange between city and country creates profit. Over time, this may lead to urban morphologies that expand this edge condition. Whereas existing cities consist largely of homogeneous development that creates few real "edges," forms such as polycentric or decentralized development maximize edge conditions (see Fig. 2).

The newfound value of the edge may encourage some suburban areas to transition back to farming and/or wilderness uses, while other areas become more urban. As the city is metabolically, economically, and spatially reconnected to the lands that support it, the urban/suburban divide disappears. The landscape becomes one of delightful urban spaces surrounded and infiltrated by productive agriculture and habitat.

Such models have been explored by Green City advocates and urban planners in the past, for example Richard Register's decentralized model[54] and Peter Calthorpe's urban network and transit-oriented development models,[55] among others. Linking such concepts with specific infrastructure decisions and economic benefits may help to provide the practical motivation for such concepts to be realized.

Conclusion

Infrastructure plays a critical role in shaping both metabolism and urban form. A waste management system based upon biodigesters would directly affect metabolic flows by closing the loop between organic wastes and food production -- a major step toward the cyclical metabolism of the Green City. In addition to these direct impacts, a biodigester-based system has cascading impacts upon city form. These secondary effects appear to be supportive of increased urban greenery, "cleaner" waste streams, increased permeability, and a city morphology that connects the city with its hinterlands. While biodigestion systems alone will not single-handedly create such sweeping effects, their positive impacts could be enhanced by supportive policy and additional investments. In this way, biodigestion systems could help to incentivize measures that have been long sought-after within the sustainable design community, but were not seen as cost-effective or of any practical value.

Some next steps for implementation and research include review of current regulations that enforce existing linear models, ban cyclical use, and subsidize regressive approaches. California's recent experience suggests that carbon pricing and reduction goals are favorable to the development of biodigestion systems. Stormwater, sewage, and garbage diversion policies also appear to be effective in starting and optimizing biodigester programs. Finally, this paper has focused on how the infrastructure decisions in extended urban food systems have changed and can change urban metabolism. To complete the green city picture, further study is needed on how the infrastructure decisions in urban transportation systems have changed and can change the extent to which urban form depletes or supports ecosystem services. Such research can help to develop a more robust model of impacts of infrastructure decisions on the city.

Historical infrastructure decisions have shaped the contemporary city, and have created an extended food system that is unsustainable. Infrastructure decisions made today will likewise shape what cities become. An extended metabolic framework, including economic flows, allows us to better understand the impacts of these decisions, in order to heal the city and achieve a sustainable urban form.

Notes

[1] This approach builds upon the work of Sabine Barles, whose metabolic analysis begins to include monetary flows. Sabine Barles, "Urban Metabolism and River Systems: An Historical Perspective -- Paris and the Seine, 1790-1970," *Hydrology and Earth System Sciences* 11 (2007): 1757-1769.

[2] Peter Newman and Jeffrey Kenworthy, *Sustainability and Cities: Overcoming Automobile Dependence* (Washington, DC: Island Press, 1999), 1. In addition to Newman and Kenworthy, this two-part definition of the green city draws from the work of Herbert Girardet, Janine Benyus, Richard Register, and many others.

[3] Gretchen Daily, ed., *Nature's Services: Societal Dependence On Natural Ecosystems* (Washington, DC: Island Press, 1997).

[4] Abel Wolman, "The Metabolism of Cities," *Scientific American* (1965): 179-190.

[5] Peter Newman, "Sustainability and Cities: Extending the Metabolism Model," *Landscape and Urban Planning* 44 (1999): 219-226.

[6] Herbert Girardet, "The Metabolism of Cities," in *Creating Sustainable Cities* (Devon, UK: Green Books, 1999).

[7] Gerald G. Marten, "Ecosystem Services," in *Human Ecology: Basic Concepts for Sustainable Development* (Earthscan Publications, 2001), http://www.gerrymarten.com/human-ecology/chapter08.html.

[8] This argument draws from economist Herman Daly's similar input-output analysis of the macroeconomic system. Herman Daly, *Ecological Economics and the Ecology of Economics: Essays in Criticism* (Cheltenham, UK: Edward Elgar, 1999), 10.

[9] United States Environmental Protection Agency (U.S. EPA), *2010 U.S. Greenhouse Gas Inventory Report*, http://epa.gov/climatechange/emissions/usinventoryreport.html (accessed Sept. 13, 2010).

[10] European Project on Ocean Acidification (EPOCA), "What is Ocean Acidification?" http://www.epoca-project.eu/index.php/what-is-ocean-acidification.html (accessed Sept. 13, 2010).

[11] U.S. EPA, "Greenhouse Gas Inventory." According to the IPCC, methane accounts for nearly five percent of global greenhouse gas emissions (www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html).

[12] For a discussion on the impacts of industrial agriculture on soil quality, see David R. Montgomery, *Dirt: The Erosion of Civilizations* (Berkeley, CA: University of California Press, 2007).

[13] United States Environmental Protection Agency (U.S. EPA), "Nitrous Oxide: Sources and Emissions," http://www.epa.gov/nitrousoxide/sources.html (last updated June 22, 2010; accessed Sept. 13, 2010).

[14] Monica Bruckner, "The Gulf of Mexico Dead Zone," Science Education Resource Center at Carleton College, http://serc.carleton.edu/microbelife/topics/deadzone (last modified Oct. 6, 2008; accessed Sept. 13, 2010).

[15] U.S. EPA, "Greenhouse Gas Inventory."

[16] Montgomery, *Dirt*.

[17] Sierra Legal Defense Fund, *The National Sewage Report Card (Number Three): Grading The Sewage Treatment of 22 Canadian Cities*, http://www.sierralegal.org/reports/sewage_report_card_III.pdf (2004), 8.

[18] Michael Pollan, *The Omnivore's Dilemma: A Natural History of Four Meals* (Penguin Press, 2006).

[19] Jeffery L. Singman, *Daily Life in Medieval Europe* (Westport, CT: Greenwood Press, 1999), 188.

[20] Rebecca Williamson, "The Breath of Cities," in *Aeolian Winds and the Spirit in Renaissance Architecture: Academia Eolia Revisited*, ed. Barbara Kenda (London; New York: Routledge, 2006), 155.

[21] Singman, *Daily Life in Medieval Europe*, 187; Williamson, "The Breath of Cities," 160-3.

[22] Williamson, "The Breath of Cities," 160. For an excellent discussion of miasmic theory, see Carlo M. Cipolla, *Fighting the Plague in Seventeenth-Century*

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[24] Matthew Gandy, "The Paris Sewers and the Rationalization of Urban Space," *Transactions of the Institute of British Geographers*, New Series 24 (1) (1999), 39.

[25] Lewis Mumford, "The Natural History of Urbanization," in *Man's Role in Changing the Face of the Earth*, ed. William L. Thomas (Chicago: University of Chicago Press, 1956), 382-98.

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[28] Sabine Barles, "Feeding the City: Food Consumption and Flow of Nitrogen, Paris, 1801-1914," *Science of the Total Environment* 375 (2007), 54.

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[30] Barles, "Urban Metabolism," 1759-60.

[31] Montgomery, *Dirt*, 183-7.

[32] Barles, "Urban Metabolism," 1760.

[33] Stephen Halliday, *The Great Stink of London: Sir Joseph Bazalgette and the Cleansing of the Victorian Metropolis* (The History Press, 2001).

[34] Gandy, "The Paris Sewers," 30. See also Barles, "Urban Metabolism."

[35] Barles, "Feeding the City," 54.

[36] Gandy, "The Paris Sewers," 29-31.

[37] Herbert Girardet, *Cities People Planet: Liveable Cities for a Sustainable World* (Chichester: Wiley-Academy, 2004), e.g., 9-10.

[38] For example, see Newman and Kenworthy, *Sustainability and Cities*.

[39] Juliette P. Bohn, Carlos Chavez, Karen Sherman, and Patrick Owen, "Food Waste Diversion and Utilization in Humboldt County," (Humboldt Waste Management Authority, 2010), http://www.hwma.net/HRFWDFS.pdf (accessed Sept. 13, 2010), 9.

[40] Bohn, et al., "Food Waste Diversion," 47.

[41] Bohn, et al., "Food Waste Diversion," 24.

[42] Bohn, et al., "Food Waste Diversion," 37-42.

[43] Bohn, et al., "Food Waste Diversion," 3, 75. Biodigesters contribute to GHG emissions reductions in two ways: they avoid methane emissions associated with landfilling organic wastes, and they produce renewable energy (Bohn, et al., "Food Waste Diversion," 74).

[44] Bohn, et al., "Food Waste Diversion," 75.

[45] Bohn, et al., "Food Waste Diversion," 74.

[46] For example, Jepson Prairie Organics creates organic compost from waste from the San Francisco area (http://www.jepsonprairieorganics.com/index.htm).

[47] Bohn, et al., "Food Waste Diversion," 69, 71.

[48] For example, see Oaktech Environmental in the UK (http://www.oaktech-environmental.com) or Recology in San Francisco (http://www.recology.com).

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[54] Richard Register, *Ecocity Berkeley: Building Cities for a Healthy Future* (Berkeley, CA: North Atlantic Books, 1987).

[55] Peter Calthorpe, "The Urban Network: A New Framework for Growth," http://www.calthorpe.com/publications/urban-network-new-framework-growth (accessed Sept. 13, 2010). See also Sim Van der Ryn and Peter Calthorpe, *Sustainable Communities: A New Design Synthesis for Cities, Suburbs, and Towns* (San Francisco: Sierra Club Books, 1986).