Nutrient Recovery

Nexus Innovation Impact Analysis

becleantech

This report has been prepared under the auspices of the Specialist Group on Sustainability in the Water Sector of the International Water Association (IWA).

CONTACT

info@becleantech.org
www.becleantech.org

DISCLAIMER

The authors and the organizations involved have no commercial interests vested in the technologies and companies appearing in this report.

CONTENTS

KEY INSIGHTS

MARKET OPPORTUNITIES

- Market opportunities for nutrient recovery range up to $145B per annum, a market Anaerobic Digestion alone can claim access to. Predominantly, the scope for recovering nutrients from animal manures is significantly greater than that from the municipal and industrial waste segments of the business.

- Anaerobic Digestion also scores highest on our Nexus Impact Index, largely because, in principle, it can achieve the largest recovery of nitrogen, together with significant amounts of energy as biogas.

- At up to some $60B each year, market opportunities for Biopower — a product of EnergyWorks — are also promising, notably in the processing of poultry litter, which itself has many desirable properties for innovations and business in nutrient and energy recovery.

- Companies with technologies serving the municipal and industrial waste segments have access to somewhat smaller markets, of up to about $40B. This also restricts their Nexus Impact Index. For these companies, extending their capabilities towards the recovery of nitrogen could dramatically change their market size.

- Businesses addressing the opportunities for recovering nutrients from all of the market segments (agricultural, municipal, and industrial wastes) — such as Eisenmann and Multiform Harvest — are particularly well placed to take advantage of future market opportunities.

ENERGY & MINING SECTOR INTERACTIONS

- Present practices for the global provision of both nitrogen- and phosphorus-based fertilizers are conspicuously unsustainable. They are highly energy and carbon intensive, especially the former.

- The energy intensity of nitrogen-based fertilizer production and the finite mineral resources of phosphorus presage ever steadily rising fertilizer prices.

- If marine extraction of phosphorus ores becomes commercially viable, the current shine on prospects for nutrient recovery may be dimmed. The same is true for nitrogen-based fertilizers: for as long as discoveries of shale gas and oil continue to keep fossil-fuel prices from rising dramatically, carbon-intensive first-manufacture N-based fertilizers will continue to dominate.

- Surprisingly, perhaps, the largest flow of nitrogen into cities (such as Atlanta and London) is that of the nitrogen in natural gas. There are species of algae capable of culture for biofuels that thrive in power-plant flue-gas environments.

- No matter how successful we might be with our low-C futures, there will always be a post-consumption market for nutrient (N and P) recovery — people have to eat, when all is said and done.

- Exceptionally, there is great synergy between nutrient and energy recovery from poultry litter. As a top-ranking entrepreneurial opportunity, poultry litter has one further advantage: chicken meat is an almost universally accepted food product in many different countries and cultures. Nutrient and energy recovery from poultry litter has to be an expanding market.

REGIONAL DIFFERENCES: TAILORING PRODUCTS TO MARKETS

- Asia leads the way in respect of growing demands for both nitrogen and phosphorus fertilizers; Africa is projected to have the biggest surplus in fertilizer production (both N and P).

- Algae Systems Integrated Biorefinery has especially promising potential to tap into all global markets, not just some regional markets.

- Regional nitrogen fertilizer production is a function of both regional fossil-fuel extraction and regional population densities. Regional distribution of P fertilizer production is a function of regional geography and geology. We therefore see business opportunities for local recovery and recycling of nutrients as greater for P-based fertilizer.

- Nitrogen-based fertilizer is best recovered as close as possible to the source of post-consumption resource flows. Phosphorus-based fertilizer is more readily recovered much further downstream in the waste-processing system.

- Distinctive regional opportunities for local recovery and recycling of nutrients are available in countries with low Purchasing Power Parity (PPP) indices.

- Regional and country-specific diets matter: ThermoEnergy and GMB International, for instance, are well placed to target the recovery of N-based products in countries where much meat is consumed; Multiform Harvest and Ostara, on the other hand, might find their better markets for recovering P-based fertilizer in countries where seeds and cereals are a large part of diets.

SCALE & POSITIONING IN NUTRIENT PATHWAYS

- 'Bigger is better' for nutrient recovery. Economies of scale can currently be exploited in (larger) centralized wastewater treatment configurations. On the other hand, recovery of nutrients from dispersed, smaller, decentralized systems is one of the grand entrepreneurial challenges for the future.

- If a company can develop commercially viable nutrient recovery technologies and services upstream, i.e., close to households, businesses engaged in the same far downstream — as is predominantly the case today — will be under serious threat.

- Companies such as Algae Systems and Ennesys have technologies for treating crude sewage. A wastewater treatment plant designed for nutrient *recovery* around Algae Systems technology, therefore, could be put in the place of today's conventional facilities for nutrient *elimination*. This would epitomize the change from today's costly pain of removing nutrients to tomorrow's profit from recovering them.

BUSINESS MODELS, RED TAPE, AND PUBLIC PERCEPTIONS

- Enterprises with the right business models and a capacity today to piggy-back nutrient recovery innovations onto low-C policies look well set for breaking into the emerging market for recovered nutrients.

- Being able to recover a great product will be of no profit, however, if environmental regulations for conventional waste streams mistakenly brand this 'great product' a 'hazardous substance'. Some red tape needs to be reworked into green tape.

- Perceptions, branding, and public acceptability can be absolutely crucial. The potential market for the Blue Diversion Toilet, for instance, looks impressive from the perspective of better global cycling of nitrogen. Having one's house re-plumbed to accommodate the toilet may be quite disruptively something else

NUTRIENT RECOVERY

NEXUS INNOVATION IMPACT ANALYSIS

By Rodrigo Villarroel Walker[1] and M Bruce Beck[2]

PATHWAYS THROUGH THE ECONOMY

The recovery of nitrogen and phosphorus nutrients from human and animal waste is an ancient practice. However, modern-day health concerns associated with the land application of this organic 'waste', together with technological advances in the production of synthetic fertilizers, have diminished the practice of waste recycling and in some instances rendered it economically unattractive and obsolete. To date, therefore, nutrient recovery has been limited and mostly the subject of academic research, albeit extensive research.

But this is changing. There are now a handful of enterprises aggressively pursuing the recovery of phosphorus and nitrogen from sewage treatment works, food manufacturing facilities, and intensive livestock production, in particular, Confined Animal Feeding Operations (CAFOs).

Phosphorus and nitrogen have very different pathways in the cycling of materials around the globe. If we track how they flow through our economies, from agriculture to our dining table to sewage, it is possible to identify how waste handling is a key element in modern nutrient cycles. Nutrient recovery from waste – a cleantech industry – is commonly associated with household waste and wastewater treatment. Innovation in these sectors has been boosted by drivers such as: (a) stricter water quality regulations, (b) the growing cost of eliminating nutrients as water pollutants, (c) rising fertilizer prices, and, to a lesser extent, (d) operational problems associated with high concentrations of nutrients in wastewater treatment, and (e) the diminishing capacity for disposing of solid waste to landfills. Other drivers of a more global nature, such as climate change, are also becoming relevant for the nutrient-recovery industry.

All in all, and in spite of the fact that these nutrients are critical for meeting the nourishment needs of the world's growing population – estimated to reach 9 billion by 2050 – it is puzzling how unsustainably nitrogen and phosphorus fertilizers are produced.

We discuss the drivers of nutrient recovery and explore the opportunities and challenges businesses and entrepreneurs may face when entering this industry. Our stance is that of technological innovation and our analysis is anchored in the framework of the water-energy-food-environment nexus. Identifying synergies and antagonisms among emerging technologies and innovations within this multi-sectoral setting are of special significance.

NUTRIENT RECOVERY

Take Figure 1, therefore. It tracks the pathways of nitrogen (N) and phosphorus (P) through the economy. It shows that there are five Areas in which nutrients can be recovered or the efficiency of their various transformations improved. There is abundant work and research on improving the efficiency of synthetic fertilizer production (Area 1) and fertilizer use in crops (Area 2). We focus, therefore, on Areas 3 through 5, thus encompassing nutrient pathways from the consumption of crops and foodstuffs – by animals and people – to discharges to the environment.

Material substitution is a well-known approach for increasing the efficiency of resource use and production. The plain fact, however, is that N and P are essential for life and their substitution is not feasible here.

[1] Research Associate at the University of Georgia and Leader, BeCleantech Initiative.
[2] Chair, Management Board, Specialist Group on Sustainability in the Water Sector of the International Water Association (IWA).

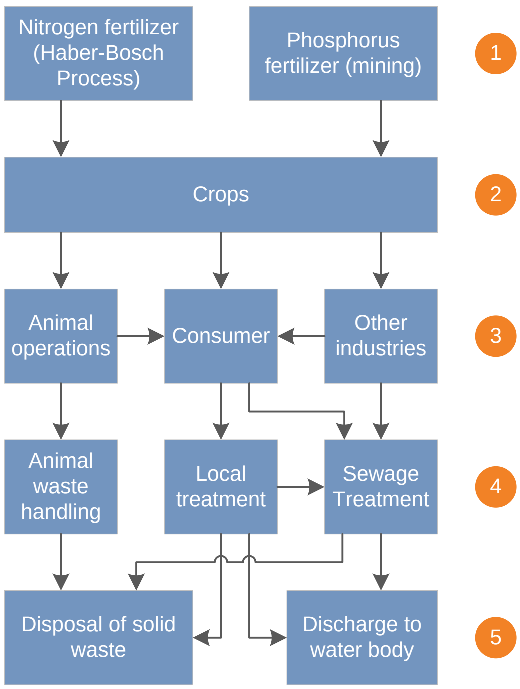


Figure 1. General scheme of nutrient pathways

Nutrient recovery commonly refers to the capture of nitrogen and phosphorus from waste flows and the subsequent production of beneficial fertilizer. Waste flows are generated from the moment food is consumed by humans or crops by animals (Area 3). We note, but will not make a point of reiterating this too often, that cities are, in effect, Confined Human Feeding Operations, i.e., CHFOs, to go alongside CAFOs. This strong similarity in 'processing' activity, we submit, can be fruitfully kept in mind.

Waste flows from consumption are collected for local treatment and disposal, such as through septic tanks and latrines, or conveyed through the sewer network to a central treatment facility, i.e., the wastewater treatment plant (Area 4). Easily overlooked, the primary role of the water in the wastewater is to convey household post-consumption residuals away from households to another (distant) location for treatment. Key to the treatment plant is the goal of preventing environmental contamination and minimizing health risks; both the water used for conveyance and the post-consumption residuals (the wastes) need to be rendered acceptably 'clean'.

Nutrient material flows are then discharged to the environment (Area 5) either in solid or liquid form. Technologies for handling wastewater effluent or solid waste (which would otherwise be sent for landfilling) are included in this Area.

To summarize, we address business opportunities in these Areas:

1. Area 3: User or consumer
2. Area 4: Treatment of waste
3. Area 5: Disposal or discharge

Table 1 lists accordingly those flows that can be manipulated or processed in order to recover N and/or P. The consequences and/or benefits of nutrient recovery have multiple ramifications extending beyond the waste and wastewater sectors. The concept of the water-energy-food-environment nexus, the *Nexus* from now on, gives us a useful template for identifying and understanding these ramifications. We conduct our technological, economic, and environmental assessment of the business of nutrient recovery within this Nexus framework.

Table 1. List of material-energy flows of interest

Flow	Description	Area
1	Fresh animal waste	3
2	Food waste	3
3	Human urine	3
4	Human feces	3
5	Industrial wastewater	3
6	Septic tank effluent	4
7	Septic tank solids	4
8	Sewage treatment plant influent	4
9	Activated sewage sludge	4
10	Sewage treatment plant internal flows	4
11	Treated animal waste	5
12	Treated sewage sludge	5
13	Sewage treatment plant effluent	5

MARKET OUTLOOK

THE FERTILIZER MARKET

To understand the fertilizer market, one needs to have a rough idea of how fertilizers are currently produced.

Global nitrogen fertilizer production is largely based on the Haber-Bosch process, where ammonia (NH_3) is synthesized through the catalytic reaction of hydrogen (typically from a fossil fuel source) and atmospheric nitrogen. Commercial phosphorus fertilizers, on the other hand, are based on phosphate rock and, in some instances, sulfuric acid (H_2SO_4), to produce phosphoric acid (H_3PO_4). The latter is the intermediate feedstock for Triple-Super Phosphate (TSP), Diammonium phosphate ($(NH_4)_2HPO_4$ or DAP), and Mono-Ammonium Phosphate ($NH_4H_2PO_4$ or MAP). Coincidentally, DAP and MAP require ammonia as a raw material.

Demand for nutrients in the global market is driven by population and income. The latter has a bearing on dietary patterns, given that a higher income status may well result in an increased demand for foods that are more fertilizer-intensive, such as meats. Historically, global demand for fertilizers has been accompanied by a more or less continuous rise in prices. The price of TSP, for example, increased from $110 in 1990 to $300 per metric tonne in 2013. That is a sustained increase of 270%. On occasion, the price of phosphate has reached $1100 (2008) and $600 (2011) due to external economic pressures. Similarly, the price of nitrogen fertilizer increased from $87 to $330 per tonne during the same 23 years, peaking in 2008 at $770 and in 2011 at $500. Given that some of the raw feedstock for nitrogen fertilizer (fossil fuels) and all of that for phosphorus fertilizers (rock) are considered non-renewable, the upward trend in fertilizer prices is unlikely to reverse, unless disruptive technologies or strategies are introduced into the fertilizer life-cycle.

Figure 2 shows that gross fertilizer use and the intensity of its application per hectare are expected to rise. More land can be expected to be dedicated to agriculture, increasing from 1.24M ha in 2010 to 1.38M ha in 2050. Fertilizer use per capita will increase from 25 kg in 2010 (with a world population of 6.9B people) to slightly more than 29 kg in 2050 (with a projected population of 9B).

In 2010, world ammonia production capacity was 158.9M tonnes (as nitrogen; N) and this is expected to increase by a further 29.8M tonnes by 2015, through the creation of 58 new urea production plants. Demand in 2015 is expected to reach only 113M tonnes N, resulting in more than 25% excess production capacity globally. Capacity, of course, does not equate to supply, which depends on other factors, such as the availability of energy and raw materials (e.g., natural gas), political stability of the country, and operational performance of the plant.

Nitrogen fertilizer production is correlated with population levels, the largest producer countries being accordingly China (33% of global production), India (11%), the United States (9%) and Russia (6%). The location and exploitation of phosphate rock does not follow global population distribution as closely as nitrogen. For one thing, Morocco alone controls 77% of global reserves with 50B tonnes, with a production of some 176M tonnes in 2010. Production of phosphorus fertilizer, however, was distributed as China first (37%), then Morocco (15%) and the United States (15%). Production of phosphorus fertilizer may well have to rise to 262M tonnes by 2050, of which 40% might be supplied by Morocco.[3]

Table 2 shows that in Latin America the nitrogen balance (supply minus demand) changes from a deficit in 2011 to a surplus in 2015. Production facilities there (supply) are being expanded faster than growth in demand. The same holds for Asia, but there because of decreasing fertilizer use (demand).

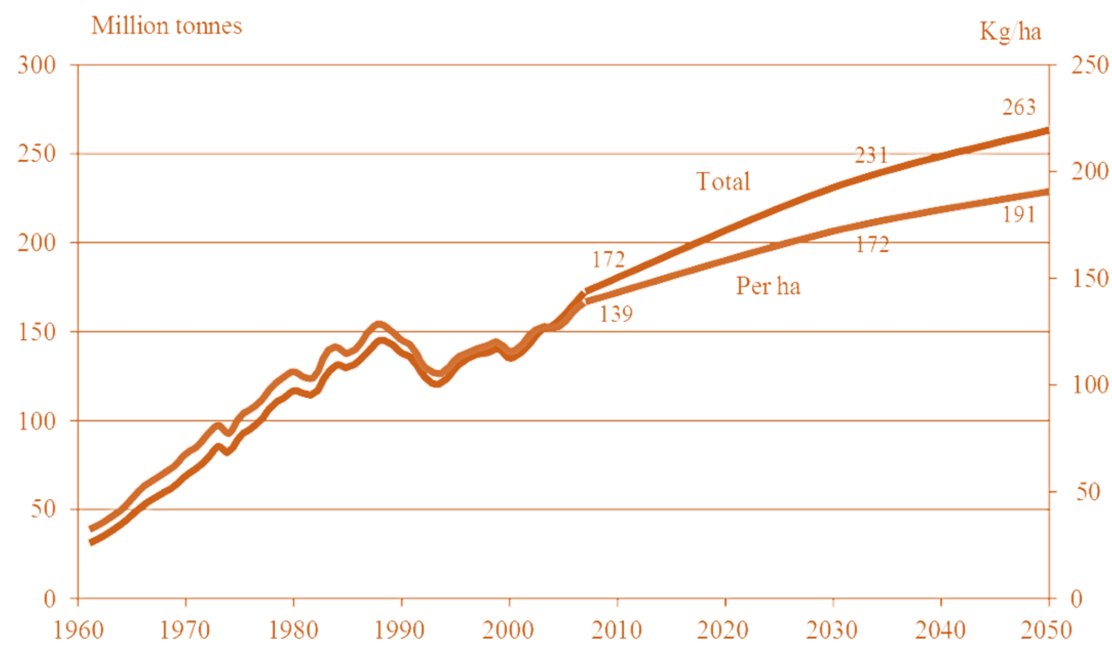


Figure 2. World fertilizer use: past and projected (nitrogen, phosphorus and potassium aggregated). Source: FAO, World Agriculture Towards 2030/2050: The 2012 Revision.

[3] Cooper, J., et al. Resources, Conservation and Recycling, 2011. 57: p. 78-86.

Table 2. Regional potential balance (demand – supply) of nitrogen and phosphorus in thousand tonnes.[4]

	Nitrogen		Phosphorus	
	2011	2015	2011	2015
Africa	1765	6411	5701	7583
Asia	-2432	1580	-4358	-4950
Europe[a]	11064	11379	394	933
North America	-6027	-6546	3071	2634
Latin America	-11	1931	-3420	-3468
Oceania	-648	-122	-240	-338

[a] Includes East Europe and Central Asia, where most of the changes in supply and demand are taking place.

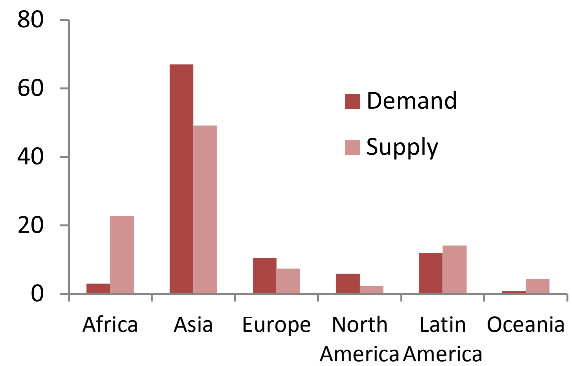


Figure 3. Regional share of growth in demand and production capacity for nitrogen fertilizer from 2011 to 2015 (as a percentage). Europe includes East Europe and Central Asia, where most of the changes in supply and demand are taking place.[4]

Increasing supply-demand surpluses in nitrogen fertilizer in Africa and Latin America are reflected in Figure 3. However, Figure 3 shows that the largest contributor to the increase in both demand and supply in the world is Asia, with the expectation that the projected surplus in Africa will be directed to meeting the needs of the Asian market.

In the case of phosphorus, Figure 4 shows that Africa is once more a region that will experience a significant growth in supply, together with Asia. Growth in demand is still dominated by the Asian market, where increasing demand continues to outstrip growth in supply. But growth in both demand and supply are also significant in Latin America. These developments contrast with the increasing deficits of phosphorus in all regions, except Africa and Europe (specifically East Europe and Central Asia). Whereas the regional pattern of demand for phosphorus is driven by population and income growth, the regional pattern of supply is governed by the geographical location of phosphorus ores.

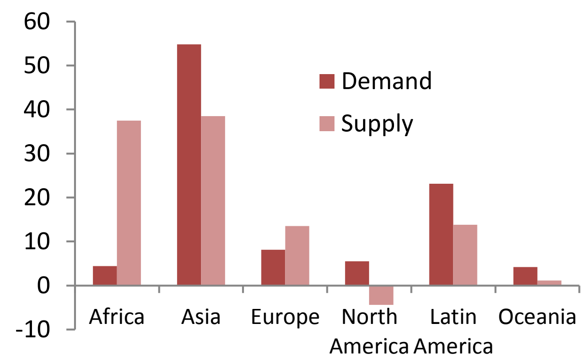


Figure 4. Regional share of growth in demand and production capacity for phosphorus fertilizer from 2011 to 2015 (as a percentage). Europe includes East Europe and Central Asia, where most of the changes in supply and demand are taking place.[4]

Upstream, then, in the nutrient pathways of Figure 1, there are substantial differences in the production of nitrogen and phosphorus fertilizers. In a globalizing world, countries take comparative advantage of their natural endowments, in extracting fossil fuels (with impacts on nitrogen-fertilizer production) or phosphate ores, with impacts on phosphorus-fertilizer production. In sum, nitrogen fertilizer production is a function of fossil-fuel extraction and

[4] FAO, Current world fertilizer trends and outlook to 2015, 2011.

population. Phosphorus fertilizer production is more a function solely of the extraction of phosphorus ores. Population distribution plays a less dominant role in the regional pattern of its upstream production.

Downstream in Figure 1, however, the regional pattern of population distribution is much more important: post-consumption nutrient flows occur where people and their animals are located. And these are the patterns (of population distribution) that will determine where the opportunities are for the business of nutrient recovery. On balance, given the slightly stronger correlation between the global pattern of (upstream) nitrogen fertilizer production and population distribution, the more immediate opportunity for 'local' (downstream) nutrient recovery and recycling will be for phosphorus recovery. The driver here is food security. It makes sense to have diversity of access to phosphorus fertilizer, especially that recovered locally.

CURRENT ACTORS

Table 3 lists a sample of technology providers and organizations currently active in the nutrient recovery business of at least one of the three Areas of Figure 1. Although not comprehensive, the enterprises listed are indicative of the distribution of commercial activity. The development of the market reflected in Table 3 is significant; such activity barely existed just a decade ago. Table 3 also provides information regarding the maturity of technological developments (bench-scale through full-scale) for the different recovery strategies. It is apparent, for example, that technologies for recovering products from (centralized) sewage treatment plants are more mature than those directed at either decentralized recovery of urine or the culturing of algae (for both nitrogen and phosphorus recovery). More detailed considerations come into play here, such as the scale of operations and social acceptability. These we discuss in our Insider Analysis.

Table 3. Illustrative technology enterprises in the nutrient-recovery industry

Organization name	Technology/Description	Maturity	Area	Flow
Nutrients PLUS	Clarus. Formulates organic fertilizers from animal manure using processes such as composting.	Full scale operation	3	1
PYTEC	BtO-Process. Based on the ablative pyrolysis principle of biomass for the production of bio-oil, biogas, and bio-char (with fertilizer properties).	Full scale demonstration	3,4	1,12
FEED Resource Recovery	High-rate anaerobic digestion (HRAD). Digestion of food waste; generates methane-rich biogas, clean effluent and high concentrate fertilizer.	Full scale operation	3	2
Eisenmann	Anaerobic Digestion (AD). Treats organic waste in the absence of oxygen. Technology used primarily for biogas generation but produces liquid and solid streams rich in nutrients.	Full scale operation	3,4,5	1,2,9
Eawag	Blue Diversion Toilet. Toilet station that separates and collects feces and urine for subsequent processing for resource recovery. The used water is treated onsite and recycled.	Pilot scale	3	3,4
GMB International	SaNiPhos. Urine processing plant. Recovers magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$).	Full scale demonstration	3	3
Ennesys	Urban Algae Culture System (UACS). Algae culture and biofuel production using raw wastewater or supernatant flow from municipal sludge digesters.	Small scale demonstration	3,4	8,10
Multiform Harvest	MultiWAS. Recovers magnesium ammonium phosphate (NH4MgPO4·6H2O) from industrial wastewater (food industry), digested animal manure, and supernatant flow from municipal sludge digesters.	Full scale operation	3,4,5	5,10,11
NuReSys Technology	NuReSys-P. Recovers magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$) from industrial wastewater (food industry) and supernatant flow from municipal sludge digesters.	Full scale operation	3,4	5,10

Organization name	Technology/Description	Maturity	Area	Flow
EnergyWorks	BioPower. Organic waste from the poultry industry is dried and then gasified to produce biogas for energy generation. Solids from gasification and incineration are used as phosphorus fertilizers.	Full scale operation	3,5	1,11
Algae Systems	Integrated Biorefinery. Municipal wastewater treatment using OMEGA[5] algae systems to recover nutrient while producing a biofuel source and soil amendment.	Unknown	4	8
Ostara Nutrient Recovery Technologies[6]	Pearl® Process. Recovers magnesium ammonium phosphate ($NH_4MgPO_4{\cdot}6H_2O$) present in the supernatant flow from municipal sludge digesters.	Full scale operation	4	10
—	Septic Tank. A future technological breakthrough for recovering nutrients from household wastewater onsite is supposed. This might include duckweed-based tilapia aquaculture and other onsite recovery systems.	Bench Scale	4	6,7
ThermoEnergy	Thermo ARP (TARP). Ammonia removal and recovery from municipal or industrial wastewater.	Full scale operation	3,4	5,8
GMB International	GMB Biodrying Tunnel. Dewatered waste activated sludge is thermally treated so that it can be used as a fuel for energy generation. The ammonia generated during the bio-drying process is captured as ammonium sulfate fertilizer.	Full scale operation	4	9
Siemens	Membrane Filtration and Reverse Osmosis (RO) systems for nutrient and pollutant removal from wastewater treatment.	Full scale operation	4	13
Universidad de Cádiz	Photobiotreatment. Treatment of wastewater using algae for biofuel production. This could be an alternative for tertiary treatment.	Bench scale	4	13
Milwaukee Metropolitan Sewerage District	Milorganite. Organic nitrogen fertilizer derived from heat-dried microbes that have digested the organic material in wastewater.	Full scale operation	5	12

[5] http://www.nasa.gov/centers/ames/research/OMEGA/index.html
[6] Other companies such Multiform Harvest, Nuresys, and Procorp (not included in this report) provide similar technologies.

INVESTMENT IDENTIFICATION

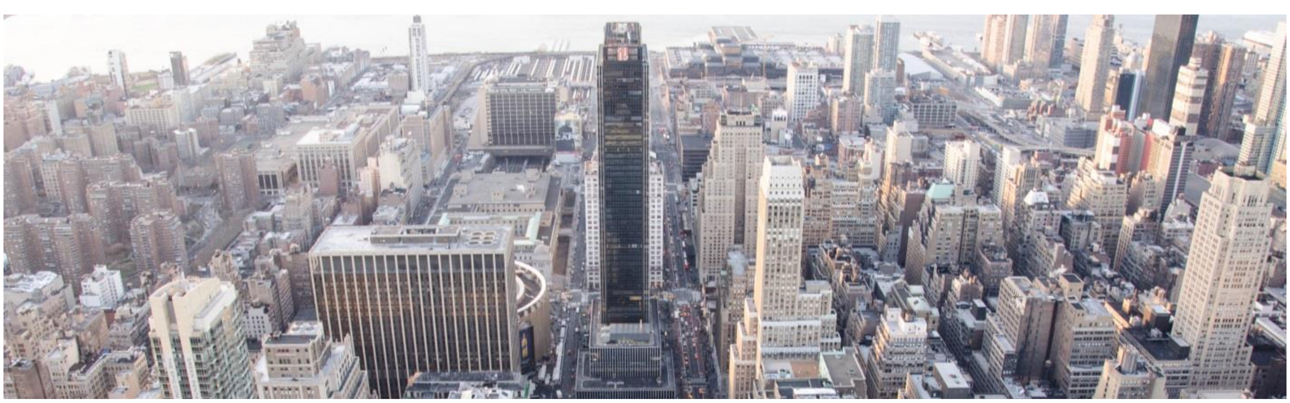
Technologies and enterprises worthy of investment need to demonstrate success in respect of the 'functionality' of the technology and the business's 'impact'. 'Functionality' directs assessment to establishing how well the technology fulfils its purpose – in addition to other technical considerations, such as adaptability, flexibility, maintenance, and reliability. 'Impact', on the other hand, has to do with assessing the extent to which the technology or enterprise adds value across all three elements of the triple bottom line, i.e., it performs well in respect of profit, planet, and people. Figure 5 and Figure 6 summarize our key findings for the sample of key actors and enterprises of Table 3. Everything boils down to our Nexus Impact Index (horizontal axis) and global Market Size (vertical axis).

Our (normalized) Nexus Impact Index is a relative measure of the potential impact of the given innovation in terms of the nexus of food (nutrients), energy, and water. The Index is assigned a value of 1.0 for that technology/business with the highest Nexus Impact among the sample of businesses and products analyzed. Values of the Index for these other businesses are therefore scaled relative to the highest-scoring technology/business. The Index captures the distinctive feature of our analysis: the extent to which an innovation or a business – albeit initially penetrating just one sector – is likely to influence benefits and savings in multiple sectors, i.e., the water, food, and energy sectors. In the present assessment, more specifically, we estimate the Index by comparing the benefits of the innovation in terms of its potential for fertilizer recovery, for avoidance of greenhouse gas (GHG) emissions, and water savings.

Potential market size in Figure 5 and Figure 6 is gauged according to the sales of fertilizer and carbon credits attaching to the given business. For any individual business in Table 3, potential market sizes range from $1 to $145B. The total market is estimated to be of the order of $235B.

The larger the size of a bubble in Figure 5 and Figure 6, the greater are the maturity of the technology and the scope of its applications. The size of the bubble signals how extensively the technology can be applied: to how many of the flows in Figure 1 and in how many economic sectors. It signals how ready the technology is for full-scale deployment.

Obvious from Figure 5 is the separation between those technologies and businesses addressing opportunities for nutrient recovery from cattle and swine (C&S) manure, and those that are not. The global market sizes for businesses recovering nutrients from C&S manure range between $60B and $145B and their associated Nexus Impact Indexes (between 0.3 and 1.0) are superior to those of the other technologies and enterprises not addressing this kind of waste. Of the two technologies of this 'C&S manure' group, Anaerobic Digestion (AD) is the more versatile and has the higher Impact Index. Its potential market size is more than twice that of the next most promising technology, i.e., BioPower. The reason AD scores so highly is that it can potentially achieve the largest recovery of nitrogen accompanied with a significant production of energy from biogas.



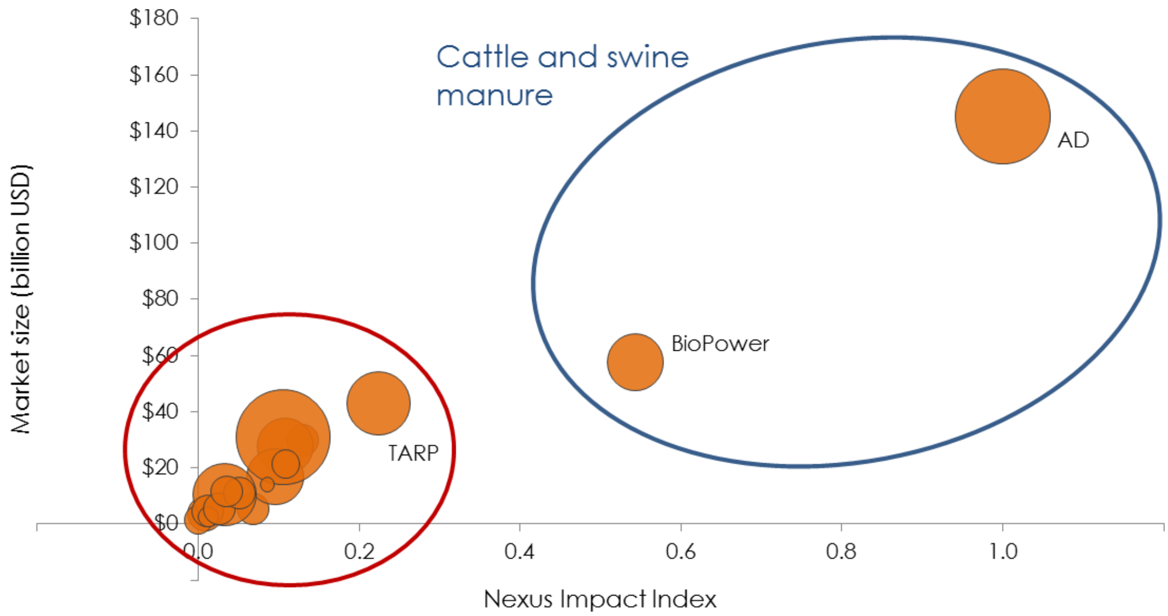


Figure 5. Technology selection across Markets and the Nexus: two major groups of technologies are distinguished, C&S Manure and Others.

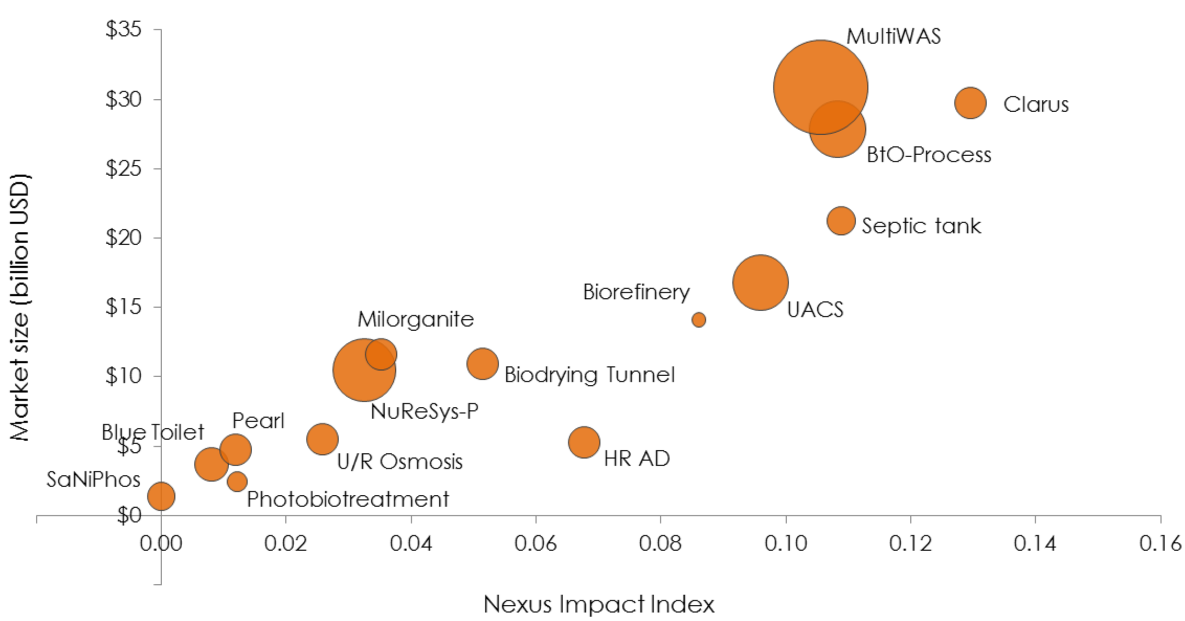


Figure 6. Technology selection across Markets and the Nexus: shown is that group of technologies not handling C&S Manure.

In Figure 5, the Thermo Ammonia Recovery Process (TARP) is the only technology not associated with C&S manure scoring an Impact Index higher than 0.2. This is because it is capable of handling both municipal and industrial wastes. Nitrogen recovery is key for the performance of this technology, in which respect it is bettered only by Anaerobic Digestion.

A clearer impression of technologies not treating C&S Manure and with a Nexus Impact Index less than 0.2 — they are mostly dealing with poultry litter, and industrial and human municipal/domestic waste — is given in Figure 6. The lower Impact Index follows from the substantial difference between the amounts of nutrients recoverable from such activities when contrasted with those recoverable from C&S Manure. Recoverable amounts of phosphorus and nitrogen from C&S Manure are between 6 and 7 times those from industrial and city flows.

Many of the innovations attaining the higher values of the Nexus Impact Index in Figure 6, for example, Clarus, Septic tank, and Biorefinery, are either less broad in their scope of application or less mature than the other technologies (such as MultiWAS, BtO-Process, and UACS). Their bubble sizes are smaller. And their lack of maturity may often be associated with a lack pre-market development funds or, frankly, a lack of public interest in their possible promise.

The Clarus process (from Nutrient PLUS) is salient in Figure 6 because it can tap into the entire global volume of litter generated by the poultry industry. Here we have a case of a very specific technology targeting just one particular Area and one particular flow in Figure 1, with, however, a potentially large market. The BtO-Process also addresses the poultry litter market, but is a technology not capable of retaining most of the nitrogen present in the waste stream. Nevertheless, its market size is not significantly different from that of the Clarus technology, since it generates an additional revenue stream from the production of fuels.

Elsewhere, we can have the situation of a large market, but no obvious technology to tap into it – a grand challenge, in fact. For example, a hypothetical innovation for recovering nutrients from septic tanks – which in reality includes any improved sanitation means other than conventional sewerage and wastewater treatment plants – shows that there are substantial benefits to be gained through nutrient recovery in decentralized wastewater handling systems.

Otherwise, we note that those technologies dealing only with the very end of the chain of waste treatment processes (Area 5 in Figure 1) have a much smaller market than businesses with products addressing other Areas and flows. For municipal wastewater effluent, this is the case for U/R Osmosis and Photobiotreatment in Figure 6; with respect to food waste, this is so for FEED Resource Recovery.

Identifying synergies and antagonisms – as we shall discuss in greater depth below in our Insider Analysis – may be the key to longer-term commercial success. For instance, technologies that recover fertilizer from sewage sludge have a great opportunity to recover the phosphorus, given the progressive 'losses' of nitrogen from upstream processing. However, their market and impact could be threatened by innovations in nutrient recovery at earlier, upstream stages in the process, such as those of the Integrated Biorefinery and Thermo ARP.

Last, but not least, we observe that nitrogen is a valuable resource, whose recovery some technologies are not properly or fully tackling (such as those of SaNiPhos, NuReSys, and Ostara). The emphasis of these technologies is on phosphorus recovery, which accordingly limits their market size in Figure 6. By way of contrast, while MultiWAS employs the same process of struvite precipitation (as SaNiPhos, NuReSys, and Ostara), it is in the business of producing fertilizer from animal (C&S) waste, thereby compensating for the inefficiency of the struvite-precipitation technology in respect of nitrogen recovery.

INSIDER ANALYSIS

Much detail and great variety in today's and tomorrow's nutrient-recovery commerce lie below the summary statistics and tabulations of the foregoing. Our presentation of this detail and variety, however, has a possibly unusual over-arching stance. The general scheme of nutrient pathways of Figure 1 reminds us of the layout of a petrochemicals complex, in which the 'Consumer' plays an intermediate, albeit central, role. The Consumer block in Figure 1 is, in fact, the central block in the diagram.

Not to put too fine a point on it, the following is the image to be kept in mind, as we proceed through this more in-depth Insider Analysis. Think of:

> The consumer as a biochemical processing node — receiving incoming pre-consumption resources and delivering onward outgoing post-consumption resources — within global networks of material-energy flows.

Markets and investment opportunities vary with the scale of operations and with geography, culture, and income status.

SCALE

We distinguish primarily between the scales of household, neighborhood, and city, to take account of the strategic drivers of (i) decentralization (and centralization) in urban utility arrangements and (ii) the presence/absence of the water-based sanitation infrastructure typical of cities in high-income countries. When it comes to nutrient recovery, we find that 'bigger is better' in today's market place.

Value Destruction — and Recovery

As the financial estimates of Box 1 show, there is a huge destruction of value in the biochemical forms of nutrients (in food) as they enter the household and leave it post-consumption. On the other hand, a city of 100,000 people – a CHFO, to recall – with the customary centralized sewerage and wastewater treatment infrastructure, can potentially generate an additional income of \$2.7M to \$4.3M each year. But being aware of the impressive value destruction in each of their households, these 100,000 citizens might then well protest: “Who owns the fertilizer my household supplies to the utility?”.

Beyond the rhetoric, innovative infrastructure and business models could enable a more immediate and tangible commercial breakthrough for nutrient recovery from residential household operations. For example, a neighborhood of 1,000 people with houses plumbed with urine-separating toilets and suitable local infrastructure could generate a recovered nutrient stream worth $6,500 on average each year.

Turning from human-feeding operations to animal-feeding operations, we do not find anything like the same high level of value destruction for the individual cow, for instance (Box 1) — and we must acknowledge here that much commercial value has gone into the fabric of the cow itself in the process. At the bigger scale, 1,000 head of cattle in a CAFO could generate of the order of $60,000 to $120,000 in annual revenues from recovered nutrients.

BOX 1

Example 1: Based on 2013 figures, a family of four in the US (two adults and two children) would have spent anywhere from $632 to $1250 for food on a monthly basis. [8] The potential nutrient value from household wastewater is about $1.0–3.5 per month.[9] If we add food scraps, the total fertilizer value could reach $1.7–4.0 per month. This does not include the potential savings in water used in toilet flushes (which could amount to about $7 per month per household). However, these figures are comparable with the cost of fertilizer for growing the food bought, between $3–8 per month. The largest portion of food cost is associated with processing, commercializing, distribution, and marketing.

Example 2: In the case of animal operations, feed and forage represent a cost of $200-800 per cow per annum (depending on the commercial purpose of the animal). The nutrient value of the cow’s manure can range from $64 to $115 per year on average. The fertilizer cost for growing the feed and forage is about $85–165.

Sewer Connectivity

It matters greatly whether a household is connected to a central, mains sewerage system. For one thing, it can be prohibitively expensive to install such connectivity. In certain areas of New Delhi in India, the city council has ceased to connect new urban developments to the sewer grid. On the other side of the world, the ongoing sprawl of Metro Atlanta in the USA has reached beyond the centralized sewer network, necessitating the use of semi-decentralized (treating less than 157m^3 of sewage per hour) and decentralized treatment systems. Although various process technologies can meet this need — a Rotating Biological Contactor (RBC), the BioKube[7] — the conventional septic tank with a drain field remains predominant.

In the mid-1990s, about 25% of all US households employed this on-site method of the septic tank with drain field, but for the purpose of disinfection (not nutrient recovery). Yet this implies about 23,000 tonnes of nutrient P and 270,000 tonnes of nutrient N passing unrecovered through such systems into the environment (on an annual basis). There is little or no regulatory incentive to do otherwise. Appropriate technologies have been explored, for example, a duckweed-based tilapia aquaculture, but while generating encouragingly high fish yields, maintaining fish health is problematic.

Sanitation

2.7B people lacking access to sanitation by 2015 is a sizeable market opportunity for adopting small-scale, on-site, decentralized treatment technologies other than septic tanks.

[7] http://biokube.com/

[8] Official USDA Food Plans. http://www.cnpp.usda.gov.

[9] Calculations use price of fertilizer for US farmers as reported by the USDA.

Urine, being virtually free of pathogens and containing a majority of the (N and P) nutrients in human excreta, offers therefore an attractive alternative material flow (in Figure 1) for nutrient recovery at source, in households and offices. Table 3 and Figure 6 identify two candidate technologies to meet this purpose, each intended for applications at different scales. The attractively branded Blue Diversion Toilet in fact separates urine from feces in either an individual household or a small community. Currently, this innovation could be integrated operationally with the SaNiPhos technology, which offers a commercially sized 5,000m^3 reactor for generating struvite-based fertilizer, albeit primarily for larger-scale applications, such as major sporting events and hospital installations. In the near future, a 'mark two' version of the Blue Diversion Toilet is set not only to separate out the urine but also to recover struvite from it – which would place it more in competition (as opposed to synergy) with the SaNiPhos product.

The bottom line is that about 1.7M tonnes of P and 20M tonnes of N are available for recovery from (human) urine on a global basis each year. These figures are equivalent to 8M tonnes of super-phosphate fertilizer and 43M tonnes of urea — some 18% and 30% respectively of current global fertilizer demand rates — and valued therefore at about \$3.2B and \$16B respectively. However, if we discount the amount of urine and feces treated onsite and in sewage treatment plants, the potential market size is reduced down to \$1.2B and \$6.1B, for P and N respectively.

REGIONAL VARIATIONS

Dietary patterns, culinary culture, and income status also matter. The cost of food varies dramatically from one region to another, with therefore a potentially significant commercial impact on the household economics of Box 1.

Production and Purchasing Power

A person in Egypt, Turkey, Kazakhstan, or Portugal produces (in urine and feces) 0.62-0.73kg of P per annum, whereas in Angola, Colombia, India, and Mongolia, for example, per capita production is but 60% of this figure.[10] Our point is this: since recovered nutrients tend to be (re-)utilized locally, their rate of production can have an impact on local food prices. On the other hand, prices of fertilizers tend to be determined by global markets. But there again, consumer purchasing power also varies widely among countries.

Take, for example, the Purchasing Power Parity (PPP) factor[11] for India, Egypt, and Gambia. It is 0.3. Farmers in these countries have to spend three times more from their earnings to buy fertilizer, relative to their counterparts in Germany, the United States, and Italy, with a PPP of 1.0 in 2013. Further local-regional elevation in fertilizer prices can result from poor distribution and ill-functioning dealer networks, with relatively high transport and handling costs from port to farm. In India, in particular, a fertilizer subsidy program of $11.3B is currently (2013-14) in place in order to compensate for such a low PPP (of just 0.3).

Local recovery of nutrients from sewage and excreta — with therefore small-scale operations (and requiring but a modest local transport and distribution infrastructure) — might greatly benefit countries with low PPPs.

Sewer Connectivity

In lower income countries only 8% of the wastewater generated is treated and wastewater handling infrastructure is sometimes non-existent. In Africa, South America, and most of Asia, less than 5% of the population is connected to a sewer network. In upper-middle- and lower-middle-income countries wastewater treatment ranges from 28% to 38%.[12] In Eastern Europe, for instance, the figure is close to 30%. This contrasts with high-income countries where about 70% of the wastewater generated is treated. Over 60% of the population in North America and Japan are connected to the sewer network. The highest connectivity in Western Europe is almost 80%. Given the global average of 0.5kg per person for the annual production of P and 3.7kg for N (excreted in urine and feces), and given continental population numbers, quick mental arithmetic will reveal the masses of N and P being directed towards what we understand as the conventional, larger-scale, less local, centralized system of wastewater collection (if not treatment).

In such systems, Algae Systems and Ennesys (Table 3) could in principle substitute their technologies for some of the core processes of conventional wastewater treatment, i.e., those of nutrient *elimination*, through algae-culturing systems. They could accordingly tap into the P and N resources there to be harvested, while enabling a carbon-neutral technological substitution and generating C-based feedstock materials for the pharmaceutical industry. The Photobiotreatment setup under development at Universidad de Cádiz offers similar performance.

Somewhat more specifically targeted (within large-scale centralized, conventional systems), ThermoEnergy's TARP (Thermo Ammonia Recovery Process) collects volatile ammonium to produce a commercial-grade solution of ammonium sulfate fertilizer. Its potential market size is a salient feature in our Nexus Impact analysis of Figure 5.

---

[10] Mihelcic, J.R., L.M. Fry, and R. Shaw. Chemosphere, 2011. 84(6): p. 832-839

[11] "The Purchasing Power Parity conversion factor is the number of units of a country's currency required to buy the same amount of goods and services in the domestic market as a U.S. dollar would buy in the United States." – World Bank

[12] Sato, T., et al. Agricultural Water Management, 2013. 130(0): p. 1-13.

Food-Waste Drivers

Growth in the world's population and consumption of food per capita can be expected to drive volumes of food waste upwards.

About a third of the edible parts of foodstuffs produced globally are wasted. At the point of consumption, consumers in Europe and North America waste about 95-115kg of food per capita per year. In sub-Saharan Africa the comparable figure is just 6-11kg. However, when pre-consumption stages of the food supply chain are included (i.e. from production to retailing), waste per capita ranges generally between 120-300kg per annum, with a world average of about 190kg. If maintained at this average level, the mass of food wasted by 2050 could reach a most impressive 1.7B tonnes each year and break through yet further upwards to a staggering 2.7B tonnes, if everyone consumed at the level of a high-income country. These figures confirm food waste as a significant driver.

With respect to nutrient (and energy) recovery from such waste, opportunities for innovation and business will need to be tailored to three strategic considerations: regional and local diets; the point along the food supply chain from which the waste is 'sourced'; and its ultimate destination (for nutrient recovery).

Specific nutrient (N and P) contents of food wastes are a function of regional dietary patterns. Companies such as ThermoEnergy and GMB International might target countries with a meat-rich diet for N recovery, while Multiform Harvest and Ostara might be interested in those with diets rich in seeds and cereals for P recovery.

In lower- and middle-income countries, 40% of food losses occur at the post-harvest and processing stages in the supply chain, whereas in high-income countries more than 40% of the losses occur during retail and consumption.[13] This difference is significant. It helps in determining which biochemical engineering unit processes or strategy could have the largest impact on reducing waste or recovering fertilizer commodities. For example, technologies such as Radio Frequency Identification Devices (RFID) are being used to improve the flow of food through production, distribution, and storage by providing real-time information on exactly what is being produced and sold. However, this will have little effect on food losses due to considerations of food aesthetics, inefficient production processes, or inappropriate 'sell-by' date specification. Technologies such as smart labelling (e.g., Oli-Tec) are directed at addressing this last and can have a positive impact on reducing waste at the retailing and consumer stage.

[13] FAO 2011 report: "Global Food Losses and Food Waste"

Knowing the distribution of contributions to waste from the different food groups will likewise have a bearing on business opportunities. For instance, in the USA, food losses at the retail stage of the supply chain (in excess of $300B in value per annum) are mostly meat, poultry, and fish, followed by the vegetable food group (17%) and dairy products (14%). Relative N and P contents vary across these food groups.

Last, the scope and mode of nutrient recovery from food waste will vary as a function of how the waste is conveyed from its source-point to the point of recovery. Consider, for instance, the possible differences in product innovations (for recovery) and their markets between: food waste conveyed to a centralized wastewater treatment plant through a sewer network fed *via* food grinders in household sinks, as one alternative; and that of truck transport to a compost heap, as another.

Irrespective of the paramount importance of reducing food waste, we conclude that deriving useful C-, N-, and P-based commodities from it is important. Food waste does not need to compete with other forms of waste for scarce landfill space. Technologies such as those offered by FEED Resource Recovery (Table 3) are already breaking through into full-scale process applications. Kroger, one of the largest food retailers in the US (and working in partnership with FEED Resource Recovery), switched recently from composting to anaerobic digestion of about 50,000 tonnes of its food wastes per annum.

BUSINESS, POLICY & SOCIETAL DRIVERS

Perceptions are all.

Escaping the High-risk/Low-reward "Black Hole"

The gravitational pull of 'nutrients as pollutants to be rid of ASAP' is mightily strong. It is unclear whether the headlong rush — towards stricter environmental regulations on the discharge of (polluting) N and P materials — is abating. It is also unclear how costly might be the 'reverse engineering' required to convert a centralized wastewater treatment plant extended to tertiary treatment for nutrient *removal*, to treatments for nutrient *recovery* instead. We know the costs of the 'forward' path to nutrient removal: between $30M and $120M to add this capability on to a treatment plant focused solely on eliminating C materials as pollutants. Undertaking the relevant full analysis of the forward and reverse engineering — on a level financial playing field — is as yet remarkably difficult.

With some confidence, however, we can expect the rising prices of fertilizers, such as those of TSP and urea in Figure 7 (and as already cited above), to be a driver of change. And by a steadily changing contrast, as we move towards the much touted 'low-C futures' for mankind, the prominence of our 'N and P futures' — and doing something 'better' about them — should grow. People have to eat, after all, low-C future or not. The longer-term upward trends in Figure 7 did not cease with the Great Financial Crisis of 2008.

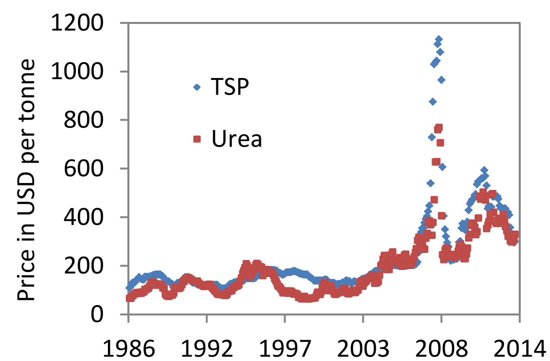


Figure 7. Prices of triple-super phosphate (TSP) and urea (FOB price)

Customary urban wastewater infrastructure in high-income countries is generally aged and aging. In the US, a $298B expenditure on renovation and renewal over the next 20 years is estimated, of which 80-85% of funds would have to be allocated to conveyance, i.e., pipes, with the remainder going to treatment. Innovations and commercial products for avoiding some of these expenditures would be attractive, notably on conveyance and, just as notably, through decentralized nutrient-recovery services.[14]

For the time being, primarily the innovative business model and some piggy-backing on policies and initiatives for low-carbon futures offer the prospect of escape from the mis-perception of 'nutrients as pollutants to be rid of ASAP'. It will help too when the red tape of environmental protection — of mis-branding a recovered post-consumption resource as a 'hazardous waste' — can be reworked to advantage.

Innovative Business Model & Product-Brand Appeal

Ostara (Table 3 and Figure 6) bases its successful Pearl® technology (for P recovery from wastewater treatment plant operations) on a well-established and widely used chemical transformation of the struvite process. Several competitors are capable of doing more or less the same thing (NuResys and Harvestform, for instance).

But where Ostara gains, in our assessment, is in its business model *and* the appeal of its product-brand.

The company's business model combines the sale of its product with a fee income from the water/sewage utility for turning the 'pain' of struvite precipitating out in the wrong place (and clogging pipes) into the 'joy' of its precipitation in the right place. In this, Ostara's success epitomizes the necessary overturning of the perception of nutrients in wastewater as pollutants 'to be rid of ASAP'.

The company's final product, clean-looking white pellets, is visually attractive and easy to handle. In one of Ostara's applications, for Thames Water in the UK, a persuasive case had to be put to the UK Trading Standards Service for the Crystal Green® product *not* to be classified as a waste. To seize the market advantage of such an appealing product, however, process operations must emphasize attainment of this appeal over maximizing nutrient (P) recovery. And this is costly, specifically in terms of pH control and the sourcing of expensive magnesium salts.

[14] Where the German sanitation industry seems especially well placed to benefit, in principle.

Perhaps less deliberately, Ostara also happens to benefit from a technology ideally suited to a minimally socially disruptive location: the wastewater treatment plant, well downstream in the flow logic of Figure 1 and usually well away from most of the public.

Societal Adoption or Rejection

So, would you have your home re-plumbed to benefit from the great virtues and advantages of the urine-separating toilet (UST) or, to give it greater brand appeal, the Blue Diversion Toilet of Table 3? It could, after all, be the metaphorical and intensely local 'nail', given which the 'kingdom' of global N recovery could be 'won'. Yet the financial inducements to do so (Box 1) do not look overwhelmingly persuasive. Perhaps too, envy at the centralized sewage utility making a fast buck from what you spent a fortune buying as food, will not be motivation enough. Intimate, private, personal habits would have to change. And a modern-day urine-centric update and upgrade would be needed for the traditional transport infrastructure for 'night-soil' removal from households.

For it is not as if we have not been here before. In 1913, 40% of Paris's human dietary N (as opposed to Paris's equine dietary N) was being recovered and recycled to Paris's hinterland to grow the food, to be returned to the city in due course[15] — today's post-consumption bread for tomorrow's pre-consumption bread, as it were. Such success in sustainable recycling was built on the foundations of a flurry of patent applications filed a century earlier. Its subsequent demise came with the increasing market penetration of the (British) WC and, we should not forget, the subsequent benefit of much greater urban public-health security.

Initial testing of the Blue Diversion Toilet in Africa has shown how the separated urine can be removed from the accompanying household cistern and transported by truck to an off-site fertilizer production facility. In parallel, Eawag is also developing the Autarky Toilet

[15] Beck, M. B. (2011). Cities as Forces for Good in the Environment: Sustainability in the Water Sector. Warnell School of Forestry & Natural Resources, University of Georgia, Athens, Georgia, ISBN: 978-1-61584-248-4, xx + 165pp (online as http://cfgnet.org/archives/587).

(the 'mark two' Blue Diversion Toilet), which tries to circumvent some of the transport issues through on-site treatment and recovery in the household. The one (Blue Diversion Toilet) relies on the economies of the relatively larger, centralized scale of operations, the other (Autarky Toilet) is oriented towards those (economics) of the smaller, decentralized scale.

Full-cost Accounting: Around the Entire Pre-consumption/Post-consumption Cycle

Waste equals food, we know: bread to bread, as it once was for Paris, synonymous with the circular flux of N — city-hinterland-city-hinterland, and so on. Affairs are more than just those of a supply chain. They are more a supply circle of pre-consumption and post-consumption flows of resources.

The demise of Paris's symbiotic urban-rural N metabolism in the early 20th century also came about (in part), because of the then recently introduced Haber-Bosch process for producing N-based fertilizer (not to mention explosives). This undercut its competitor processes, in particular, those of resource recovery from human waste in the city. Today, the N cycle of the urban metabolism begins with the expensive, energy-intensive incorporation of nitrogen gas from the atmosphere into fertilizer and ends with the expensive, energy-intensive expulsion of nitrogen gas back to the atmosphere — from wastewater treatment for nutrient pollutant *elimination*. But no-one 'costs out' this energy-wasteful cycle from beginning to end (beginning to beginning, in fact).

Nutrient recovery is going to have to punch its way into the fertilizer market with one hand tied behind its back. The full costs of fossil-fuel GHG emissions in the case of customary N-fertilizer production, and mining impacts for conventional P-fertilizer production, are not currently taken into account. The costs of discharging 'unwanted' nutrients into the environment — $56 in damages to the fisheries of the Gulf of Mexico per kilogram of N discharged, for instance — are not accounted for.

Will they ever be?

The Desperate and the Outlandish?

The situation is becoming almost bizarre. We hear of 'peak oil' and – admittedly, less so – 'peak phosphorus'.

As in the long-term evolution of the oil and gas industry, where techniques and technologies have been developed to enhance the recovery of progressively less readily extractable resources from more challenging geologies and geographies, the mining industry is starting to examine the prospects for deep-ocean P recovery. Chatham Rock Phosphate Ltd[16] is carrying out the Chatham Rise Project, 450km off the coast of New Zealand. Namibia Marine Phosphate[17] has begun its Sandpiper marine phosphate project, 60km off the coast of Namibia. Do these things smack of desperation?

In contrast, and in dramatically more mundane and much less grandiose terms, P is being recovered from the sewage of Durham, Oregon (using Ostara's technology). The pelletized slow-release fertilizer is being bagged and transported some 450km over the border to Vancouver Island, British Columbia, there to be dumped — against the odds of half a century of conventional water pollution control — in order to arrest the decline of salmon populations. The challenge is to enable the salmon fry, in the absence of the once plentiful P-rich, rotting carcasses of the adult salmon, to incorporate sufficient P so as then to survive their subsequent migration from the freshwater environment to — where else — the marine environment. How outlandish, how far-fetched, does this seem?

Some 'rational' argument, somewhere — but not necessarily the rationale of a strictly financial incentive — can make the change happen for nutrient recovery *and* the restoration and enhancement of what we call ecosystem services.

[16] http://www.rockphosphate.co.nz/
[17] http://www.namphos.com/project/sandpiper

Towards More Pragmatic Economics for the Environment

The hardest-nosed economic rationales surrounding C, N, and P flows in the environment are presently those of cap-and-trade, or Nutrient Trading Credit (NTC) markets.

In the Chesapeake Bay watershed in the USA, the local (state) Pennsylvania Department of Environmental Protection (DEP) is working with the Pennsylvania Infrastructure Investment Authority (PENNVEST) to sustain an NTC program.[18] Within the program, manure-to-energy conversion company EnergyWorks (Table 3) is trading its credits with water utility companies within the range $2–4 per N/P 'credit'. This income stream to the company derives from the fact that for each MWh of energy generated, 35 credit-worths' mass (lbs, in fact) of N and 2 credit-worths' mass (lbs) of P are *no longer* being discharged as pollutants to the environment. EnergyWorks is removing poultry litter from the land – where previously the N and P would have been available for mobilization in runoff or leachate, hence for pollution of the aquatic environment. Similar NTC markets are operating in Ohio, Virginia, Connecticut, Minnesota, and North Carolina.

Here the significance of scale is revealed in another dimension. Unlike cap-and-trade programs for CO_2 emissions (the C-credit market), whose impact and extent are global, many of the adverse environmental impacts of P and N are manifest at a more local scale. The attaching NTC market is smaller in size and in number of actors (buyers, sellers), but on the other hand, it is an easier market to regulate. Nevertheless, it struggles to be supported administratively by cash-strapped local (state) governments and agencies.

[18] http://www.portal.state.pa.us/portal/server.pt/community/nutrient_credit_trading/19518

Institutional Investors, the Carbon Bubble — and a Phosphorus Bubble?

The Carbon Tracker Initiative (CTI)[19], with its popular headline concept of a 'Carbon Bubble', has recently shot to prominence. Presuming governments may well eventually take action to bound rises in average, global temperatures to no more than 2 degrees Celsius, this implies that only some 20-40% of the world's currently proven reserves of fossil fuels can be burned. 60-80% of the reserves of fossil fuels currently held by businesses in the fossil-fuel prospecting and extraction sector are, in effect, worth $0.0 (or so the argument runs).[20]

What institutional investors can do about this is the punch-line of CTI's *Unburnable Carbon 2013: Wasted Capital and Stranded Assets*. If investors were to divest *en masse*, stock exchanges around the world could suffer significant falls in their indices, depending upon their exposure to the volumes of fossil-fuel sector stocks quoted on those exchanges. The 'carbon bubble', therefore, is already with us: in the latent run-up in stock prices of fossil-fuel companies. There is some anticipation, therefore, of the bursting of this bubble.

We might fear (or welcome) the same for Chatham Rock Phosphate Ltd or Namibia Marine Phosphate — except that acquiring P to fuel the food chain, unlike the combustion of C-based materials to generate energy, is not known to have any substitutes.

What we are discerning is not so much hard, pragmatic decisions being determined by some monetizing of the value of natural-capital assets and the profit streams of their ecosystem services, but rather decisions guided by what pension funds, for example, judge will (or should) eventually generate the incomes of those of us fortunate enough to have a pension to cover our retirement.

[19] www.carbontracker.org
[20] http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/02/PB-unburnable-carbon-2013-wasted-capital-stranded-assets.pdf

NEXUS: SYNERGIES & ANTAGONISMS

Nutrient recovery is deeply intertwined with energy recovery. Consideration of the one cannot be divorced from consideration of the other. It matters where N, P, and C are flowing in richer, more concentrated fluxes in the 'petrochemicals complex' of Figure 1.

Our *Insight*, after all, is a *Nexus* Impact Analysis, not a water-sector or energy-sector or food-sector analysis. The best business and innovation opportunities are going to have to be identified in situ, as it were, from within the irreducibly complex entanglement of the water, energy, and food/agriculture sectors — from within the petrochemicals complex of Figure 1. It matters what business intervention where affects beneficially or adversely other business interventions elsewhere in the complex. It matters what business intervention can prosper in the water *and* energy *and* food (and other) sectors.

Some Basic Facts of Life

In contrast to cattle, pigs, sheep, poultry, and so on, source-separation is possible for humans. Nutrients N and P predominate in urine. Feces are rich in C (and pathogens), hence their basis for generating energy. Source separation matters. CAFOs differ from CHFOs in this essential materials-processing feature. Globally, 1.7M tonnes of P and 20M tonnes of N are contained in the annual flow of human urine. The corresponding figures for feces are 1.5M tonnes of P and just 5.2M tonnes of N. The associated carbon is about 45M tonnes, of which about 90% is volatile and can be used for energy generation. However, both the market and Nexus Impact for city-derived commodities are significantly less than those for CAFO-derived products (Figure 5).

From a technology perspective, if renewable biofuels are to be produced as the intermediate for generating energy, the N and P (from urine) will require re-combination with some C (from feces or the atmosphere, i.e., CO_2).

If and when it comes to recovering either energy or nutrients from post-consumption animal metabolic products and pre-consumption food waste, recovery of energy will generally prevail.

Perhaps, however, there are specific contexts in which this is not an either/or competition. Recovery of P can be compatible with the recovery of energy, in specific contexts.

Nutrient-energy Synergy: Poultry Litter

Poultry litter, in our opinion, is better suited to technological innovations of a less conventional nature. It has both a low moisture and ash content.

With gasification (e.g., EnergyWorks in Table 3) and pyrolysis (PYTEC in Table 3) the litter can be converted into biofuels for energy generation and transportation along with a solid-phase bio-char suitable as a soil amendment with yet nutrient value (albeit weak in respect of its N content). Unlike conventional incineration, particulate matter injurious to human health is not emitted with either the gasification or the pyrolysis technologies.

Synergy between nutrient and energy recovery derives here from the general resistance of P compounds to being mobilized in gaseous form, hence their concentration in the bio-char. Put another way, P derives from the earth and returns to it, whereas N is taken from the atmosphere and returned to it (as we have already seen). Labile and 'volatile' N is always liable to escape its otherwise productive capture in biochemically active non-gaseous forms.

In terms of the more restrictive capacity of nutrient recovery in the absence of energy recovery, Nutrients PLUS, for instance, composts poultry litter in a relatively conventional manner. Its product is a balanced mix of synthetic (inorganic) and organic fertilizer, with therefore the desirable property of a slower release of nutrients in its application relative to a 100% synthetic fertilizer. For all the popular appeal of composting, however, it suffers from one key disadvantage as a technology: it fails to recover some 40% of the N in the feedstock.

As an entrepreneurial opportunity, poultry litter has one further advantage. Given the widespread presence of chicken in many culinary traditions and the shift towards higher-protein, meat diets, poultry litter can be expected to be a growing business. In contrast to food waste, pressures on confining its growth are unlikely.

Global poultry meat production was expected to increase by more than 33% from 2011 through 2022. Figure 8 shows the corresponding predicted upward trend in poultry-litter production, to more than 150M tonnes by 2022, hence our identifying it as an expanding market. Regional breakdown is as follows (for 2011): 66% for Brazil, China, EU-27, and the USA, but decreasing to 62% by 2022, as poultry production increases in south-east Asia (India, Pakistan, Vietnam, and Saudi Arabia).

Nutrient-energy Synergy: Urban Solids

Notwithstanding our capacity to generate separated liquid- and solid-state post-consumption resources (both biologically and technically), the conventional WC and sewer do not exploit this capacity. In the customary urban infrastructure of high-income countries, separation is deferred until the distant, downstream sewage treatment plant, where the production of (separated) urban solids has generally increased with increasingly more stringent environmental regulations on the liquid effluent discharge to the environment (Figure 1, Area 5).

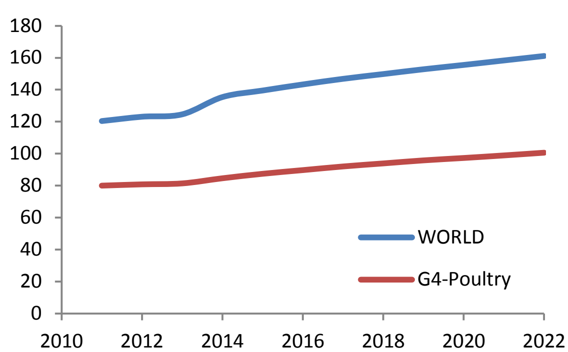


Figure 8. Projection of poultry litter production (in million tonnes) in the poultry meat industry, where G4-Poultry includes Brazil, China, EU-27, and the USA.

Gathered around the supernatant (liquid) by-product of anaerobic digestion (AD; Table 3 and Figure 5), Ostara, Procorp, and Multiform Harvest (Table 3) are all companies mobilizing struvite crystallization for P and N recovery. The AD supernatant is relatively rich in P (about 6-10mg per litre, as phosphate) and N (about 100-130mg per litre, as ammonium). Conventional operation is to return this AD supernatant back to the liquids processing train, where struvite precipitation can readily cause the clogging of pipes unless suppressed by expenditures on aluminum and iron salts. Companies like Ostara, Procorp, and Multiform Harvest will profit therefore from promoting the precipitation of struvite in the 'right' place (in the AD supernatant).

Otherwise, a principal product long harvested from AD — a conventional unit process for handling the solids separated at the treatment plant — has been methane gas for heat and electricity generation.

Thus there is here a synergy between nutrient recovery and energy recovery from the urban solids separated downstream. Much the same kind of synergy, built on the same technology platform of AD, can be exploited in the treatment of (fresh) animal manure from CAFOs. In this application, however, the recovered organic fertilizer is the liquid-solid product of digestion, not that derived from manipulation of any supernatant by-product (of which there is none).

Upstream-downstream Antagonisms: Urban Sewage Infrastructure

The fact is, however, *if* a company can build up a successful business in recovering nutrients upstream in the urban sewage infrastructure — as far upstream, in principle, as the individual household — the business of commercial recovery of the same far downstream (in the treatment plant) has to be under threat.

NuReSys, Multiform Harvest, and the Blue Diversion Toilet (Table 3) all address the upstream market for nutrient recovery, from both the residential sector and the industrial sector. We have already noted how development of the Blue Diversion Toilet is now aimed at 'self-sufficiency', in the sense of separating flows of urine and feces and recovering fertilizer and energy from them (respectively). This development may render the SaNiPhos product/technology less attractive.

Nutrient-energy Synergy: The Case of N

In spite of the downsides of labile N, synergy between nutrient and energy recovery *is* possible for N-based materials: for the one specific, but widespread, technology of AD (Table 3 and Figure 6); and for the relatively N-rich manures from cattle and swine production.

Aerobic digestion is frequently used for the safe *disposal* of these manures, since it requires less capital and has a simpler operation, with the resulting products being therefore purposefully low in their organic (C) and N contents. In contrast, N is beneficially retained in the liquid and solid products of AD, while C is captured in its gaseous products and used as a fuel (methane) to generate heat and electricity. Eisenmann (Table 3) is one of the companies offering such AD applications for the cattle and swine manure sub-sectors. Their liquid and solid products are rich in organic (as opposed to synthetic) nutrients.

Nutrient-energy Antagonisms: Upping the Barriers to Market Entry

Contemporary developments in the extractive and mining industries threaten the market opportunities for both P and N (nutrient) recovery. For P, access to the raw feedstock (in rock) is driving exploration seawards to once unthinkable places, when yet much of the (post-consumption) resource resides onshore and close to home. For N, burgeoning, cheap access to oil and gas reserves will sustain economically the energy-intensive (hence carbon-intensive) Haber-Bosch process.

For both – N and P recovery from CHFOs and CAFOs, that is – these developments will raise the thresholds for entry into the fertilizer market. The greater challenge, arguably, is to the prospects for N recovery. The drama of marine extraction of P and the finiteness of P resources will give this element a higher popular, public profile than the renewable nature of N, whose 'renewability' (as fertilizer) is actually massively expensive and energy-intensive, hence far from qualifying as 'low carbon'. Both threats are those of *seemingly* cheap extraction and manufacture. Both, in their headline terms, overlook the opportunities for real savings in transport costs, from local recycling of post- and pre-consumption resources on a small scale (as opposed to the costs of global transport for conventional first-manufacture P and N resources).

Straight Nutrient Recovery

Contrary to what might by now be expected, there *are* alternatives to anaerobic digestion (AD). The process of 'biodrying' is one of them, in which the drying of activated-sludge biomass is undertaken at high temperatures, from 60 Celsius up to 500 Celsius, depending on the specific process. Milwaukee Metropolitan Sewerage District (MMSD), Siemens, and GMB International (Table 3) all recognize the nutrient value of the ubiquitous activated sludge process, which is at the heart of the modern centralized wastewater treatment plant. Milorganite — MMSD's branded organic fertilizer (Figure 6) — has been on sale since the 1930s. It contains 5% N and 2% P as its active components. Siemens, with its IPS Composting System, and GMB International, with its GMB Biodrying Tunnel, aerate the biomass in order to generate a biochemically stable product.[21] However, the Biodrying Tunnel technology is the only one that deals with nitrogen losses during the drying process, by capturing it as sulfate ammonia. Its market and Nexus Impact Index are indicated by the Biodrying Tunnel bubble in Figure 6.

In GMB International's Biodrying Tunnel a ventilation system collects the gaseous ammonium driven off the heated biomass as it dries, thus benefitting, on this occasion, from the labile character of N. The ammonium is then converted into a liquid ammonium sulfate fertilizer. In fact, should it so wish, GMB International could boast of a synergy here in nutrient *and* energy recovery. It advertises its dried solid product as having an energy content (about a third of that of anthracite coal) recoverable from subsequent incineration.

[21] Composting is widely applied for similar reasons in stabilizing CAFO manures and rendering them pathogen-free. The resulting product is rich in P, not least because much of the N content (as ammonia, for example) is evaporated off in the process.

Straight Energy Recovery

Feces, being relatively rich in C (in contrast to urine), are a target for energy recovery. Digestion of human fecal matter can produce biogas (methane) and generate electricity, as already seen above for the AD process applied to urban solids. Accordingly, developments of suitable products, at the small and intermediate scales, upstream and downstream in the infrastructure, are several, for example: the Bioelectric Toilet from the University of Colorado (upstream, small scale, decentralized); and the Fecal Sludge-fed Biodiesel Plant of Columbia University (downstream and larger scale). As with all such 'smaller-scale' innovations, current markets are those where the customary, centralized, water-based paradigm of sanitation and sewerage is not in place.

In the end, at the end of the flowpaths of Figure 1 (Area 5), there may be much solid-state 'waste' to be 'disposed of'. In spite of all the beneficial nutrient and energy recovery that may have been achieved in the upstream processes (Areas 4 and 3, Figure 1), some of this waste may yet bear residual energy to be harvested. Incineration of separated sewage sludge is the oft-preferred treatment in high-income countries. In general, about 17kWh of thereby generated electricity can be expected per capita each year. Greater London, for instance, incinerates all of its sludge.

BEYOND THE WATER SECTOR

Whereas it has been self-evident — within the water-food-energy nexus — to chart the markets and business opportunities for nutrient recovery deriving essentially from our need to eat; and whereas so many of these opportunities reside in manipulating differently the post-consumption resource flows co-mobilized with the water of the urban sanitation systems of high-income countries — so that these business opportunities appear to be opportunities within the water sector – it is a fact that some of the largest flows of N and P in the urban metabolism are ones conventionally allocated to the energy sector.

Nutrient Recovery from the Energy Sector

To begin with, the flow of natural gas, when widely used (as it is) for either energy generation or transport, hides the fact that this is the largest flow of N in some cities. For example, in Atlanta, USA, and London, UK, this flow amounts to 20,000 and 35,000 tonnes of N each year respectively (including nitrogen oxides and molecular nitrogen). Combustion of natural gas liberates this N as gaseous nitrogen oxides and contributes thus to acid rain, GHG emissions, and the prospect of (future) costs to human health, estimated to reach as much as $23 per kilogram of N released.

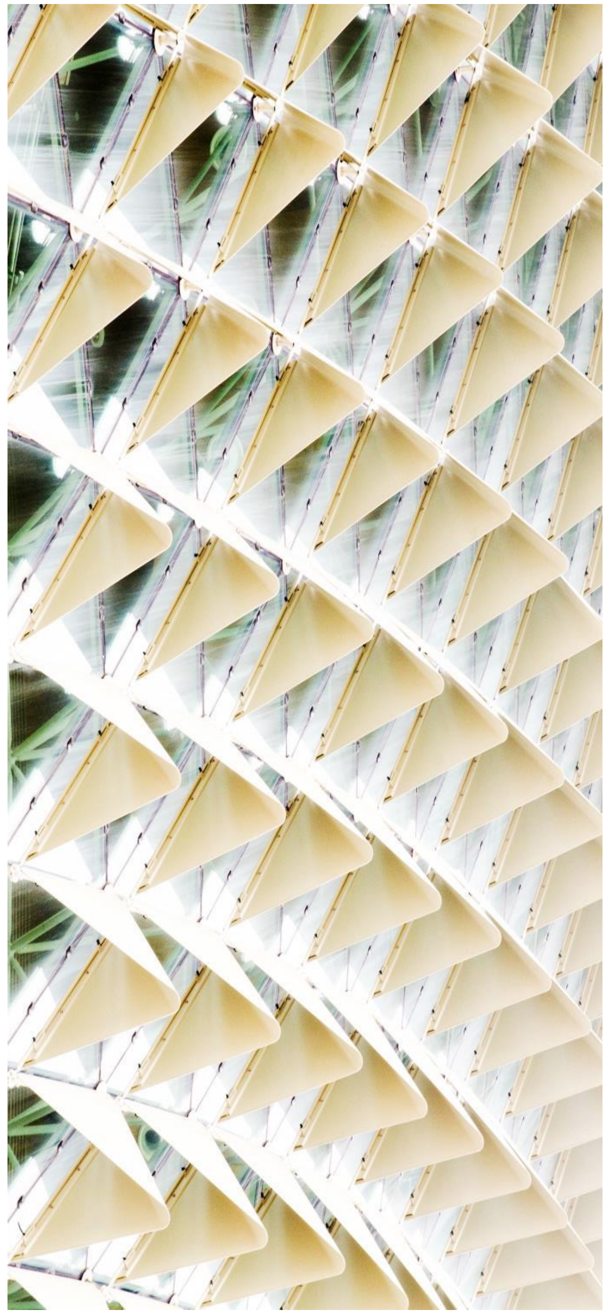
Commercial biotechnology for algal biomass culture, which is central to the Biorefinery technology (Figure 6), is one such opportunity for capturing the labile N in the combustion products of natural gas or coal. In particular, the species of algae *Heterosigma akashiwo* can flourish in a power-plant flue-gas environment, where its growth will benefit from the plentiful C in the combustion product of CO_2.[22]

On the other hand, coal, hence post-consumption coal ash, bears a significant amount of the non-volatile, earth-to-earth P. The application of coal ash to soil both adds to the soil's P reservoir and increases the soil's capacity to retain such P for subsequent plant uptake.[23]

Carbon Trading Within the Nexus

The whole purpose of a Nexus Impact Analysis is to recognize facts on the ground. It is hugely useful, successful, and convenient to separate the world into the constituent parts of its economic and technological sectors. But there is also a time and a place for taking the complementary 'systems perspective': to examine the cross-sectoral impacts of an innovation at one locus in the nexus; and to examine the system-wide ramifications of part-to-part synergies and antagonisms, to be encouraged and discouraged respectively. Assessing the markets and investment opportunities attaching to nutrient recovery from the water sector has been a timely and salutary place to commence BeCleantech's Nexus Impact Analysis.

We know from the foregoing how local nutrient recovery, in its substitution of some of the (otherwise) conventional first-manufacture N and first-extraction P, has substantial implications for energy savings, hence C emissions, with global extent, when fertilizers are transported to their place of application from afar. Ostara claims that struvite production in a city's sewage treatment plant results in reductions in emissions of more than 50% in gaseous C oxides and N oxides (as well as S oxides) and of a more than 80% lower rate of GHG emissions.[24] This is most credit-worthy.



[22] http://ens-newswire.com/2013/07/02/it-takes-a-special-algae-to-make-biofuel/

[23] CRC CARE Technical Report 26: Phosphorus management in soils using coal combustion products

[24] On a carbon dioxide equivalent (CO2E) basis compared with traditional fertilizer manufacture.