Closing the food loops: Guidelines and criteria for improving nutrient management

Citation for the original published paper (version of record):

Mc Conville, J., Drangert, J., Tidåker, P. et al (2015)
Closing the food loops: Guidelines and criteria for improving nutrient management
Sustainability: Science, Practice, and Policy, 11(2): 33-43
http://dx.doi.org/10.1080/15487733.2015.11908144

(article starts on next page)

Sustainability: Science, Practice, & Policy
http://sspp.proquest.com

ARTICLE

Closing the food loops: guidelines and criteria for improving nutrient management

Jennifer McConville[1], Jan-Olof Drangert[2], Pernilla Tidåker[3], Tina-Simone Neset[2], Sebastien Rauch[4], Ingrid Strid[5], & Karin Tonderski[6]

[1] Department of Architecture, Chalmers University of Technology, Sven Hultins gata 6, Gothenburg, SE-41296 Sweden (email: jenmcc@chalmers.se)
[2] Department of Thematic Studies-Environmental Change, Linköping University, Linköping, SE-581 83 Sweden (email: janolof.drangert@gmail.com; tina.schmid.neset@liu.se)
[3] Swedish Institute of Agricultural and Environmental Engineering, Box 7033, Uppsala, SE-750 07 Sweden (email: pernilla.tidaker@jti.se)
[4] Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, SE-412 96 Sweden (email: sebastien.rauch@chalmers.se)
[5] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, Lennart Hjelms väg 9, Uppsala, SE-750 07 Sweden (email: ingrid.strid@slu.se)
[6] Department of Physics, Chemistry, and Biology, Linköping University, Linköping, SE-581 83 Sweden (email: karsu@ifm.liu.se)

As global consumption expands, the world is increasingly facing threats to resource availability and food security. To meet future food demands, agricultural resource efficiency needs to be optimized for both water and nutrients. Policy makers should start to radically rethink nutrient management across the entire food chain. Closing the food loop by recycling nutrients in food waste and excreta is an important way of limiting the use of mineral nutrients, as well as improving national and global food security. This article presents a framework for sustainable nutrient management and discusses the responsibility of four key stakeholder groups—agriculture, the food industry, consumers, and waste management—for achieving an effective food loop. In particular, we suggest a number of criteria, policy actions, and supporting strategies based on a cross-sectoral application of the waste hierarchy.

KEYWORDS: Food processing industry wastes, agricultural wastes, waste utilization, food additives, material balance

Introduction

The global population has grown sharply over the last century, placing increasing burdens on the natural resources that provide us with food, energy, and shelter. Roughly one third of food internationally produced for human consumption, equivalent to 1.3 billion tons per year, is lost or wasted (Godfray et al. 2010; Gustavsson et al. 2011). Estimates of the volume of food wasted along global supply chains, from agricultural production to final human consumption, range from 25–50%. There are great differences among regions in the amount of food lost and in terms of where the losses are most pronounced (Mena et al. 2011). In all regions, however, there is growing recognition of the need to improve agricultural resource efficiency with respect to both water and nutrients (Foley et al. 2011). Increasing access to fertilizers, particularly locally produced agricultural additives, and improved soil-nutrient management are critical in assuring global food security (Chen et al. 2011).

Increased productivity since World War II has been achieved through application of chemical fertilizers, pesticides, and irrigation, yet the contemporary global environmental situation and growing constraints in resource availability challenge us to take a more sustainable approach. The production of chemical fertilizers relies on limited sources of phosphorus and energy-intensive nitrogen fixation. Both nitrogen and phosphorus cycles have been identified as critical planetary boundaries for maintaining a balance in the Earth's biophysical processes (Rockström et al. 2009). Currently, cycles for these two elements are under threat in many parts of the world where reactive nitrogen from fertilizer production ends up polluting waterways or is released as a greenhouse gas (nitrous oxide), and excessive use of phosphorus not only reduces access to this limited resource, but phosphorus runoff causes eutrophication of lakes and puts oceans at risk for anoxic events. Better management of these macronutrients is needed both from an agricultural perspective in terms of, for example, reducing fertilizer runoff and with respect to the global environment by managing material flows of these elements. At the same time, it is important that we devote more attention to the role of micronutrients and soil organic carbon in enhancing productivity.[1] Studies show that an increased soil organic-carbon pool can influence yields (Lal, 2006) and that many micronutrients enhance disease resistance and tolerance (Dordas, 2009). The recycling of organic waste has the potential to return both carbon and nutrients to soils.

The planetary boundary for nitrogen has already been exceeded and that for phosphorus is threatened (Rockström et al. 2009). It is time to radically rethink nutrient management across the entire food chain. Scientists see recycling of nutrients in food waste and excreta, for example, as an important way of limiting the use of mineral nutrients as well as improving national and global food security (Cordell et al. 2009), particularly if such measures can balance local and regional nutrient flows. Improving global nutrient management will require a holistic approach that includes the entire food cycle from production and distribution to consumption and resource recovery. There is a need for guiding principles and actions that reach a broad spectrum of stakeholders in diverse sectors and unite them in a global vision for sustainable nutrient management. Taking this broader approach means linking material flows and management sectors that today are generally managed on a separate basis, such as food-processing plants and wastewater-treatment facilities.

This article aims to influence policy development by presenting a working framework for sustainable nutrient management based on multi-stakeholder collaboration. Current models for sustainable waste and material-flow management highlight the need for waste prevention, recycling, and life-cycle perspectives. Building on the popular waste hierarchy, while recognizing the need to focus on waste minimization (Price & Joseph, 2000), our framework is based on two key principles: 1) increasing the effectiveness of nutrient use in the overall provisioning system (i.e., minimizing waste flows) and 2) closing the loop on fertilizing nutrients (i.e., reuse & recycling). The second principle also entails ensuring that nutrient-flow streams are kept free from contaminants so that the constituent resources can be reused. This article presents a number of criteria, policy actions, and supporting strategies, for stakeholders at all levels of the food chain, for achieving the goal of sustainable nutrient management. The text explains the theoretical framework based on a multi-sector approach to food loops and the waste hierarchy. The framework is then presented with discussion of the roles of each sector. Finally, specific policy strategies and methods for enabling change are discussed.

[1] Micronutrients are those elements essential for plant growth that are needed in only very small quantities, as opposed to macronutrients (nitrogen, potassium, phosphorus, calcium, magnesium, sulfur) that are required in larger quantities.

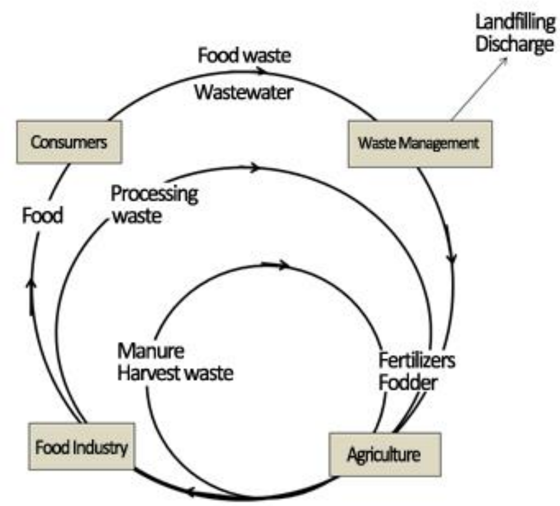

Figure 1 Food Loops: from agricultural production and processing to consumption and collection/treatment of food waste so as to return valuable organic and mineral compounds to agriculture. *Note to readers*: this article focuses on the larger loop in which food passes through all four sectors.

Theoretical Framework

The sustainable management of nutrients means achieving a balance between the removal and addition of organic and mineral material. Such practices also entail avoiding the net accumulation of heavy metals and other undesirable compounds, such as medical residues and pesticides, in soil. This article uses a framework based on three concepts that aim to capture the complexity associated with the formulation of sustainable solutions: food loops, a multi-sector approach, and the waste hierarchy.

Food Loops

To maximize resource efficiency, it is necessary to adopt a life-cycle perspective with respect to nutrient flows within the food system. Closing food loops means the nutrients are recovered and returned to agriculture to the greatest extent possible (Figure 1). Food loops exist at several levels and may connect one or more sectors. For example, the internal agricultural loop returns manure and harvest waste to the fields, while other loops transport food products from fields to consumers and on to waste-treatment plants. However, each sector tends to focus on its own agenda and thus cross-sectoral collaboration for nutrient management is a weak point in many policies today. Therefore, this article focuses on the larger loop in which food passes through four key sectors (further explained in the section below).

From an environmental perspective, closing loops is best done at a local scale to avoid unnecessary transport and associated energy costs (Tidåker et al. 2007). However, we recognize that global population distribution and local food production capabilities can make it difficult, and perhaps economically inefficient, to maintain a completely local food loop. Thus, there will be tradeoffs to consider when determining the optimal scale of this system. For example, it is unreasonable to expect that large cities can be completely supported by urban and near-urban agriculture. The optimal scale of the food loop for a particular city will depend on the consumption patterns of the city and local agricultural conditions.

Multi-Sector Approach

Four key management sectors are involved in the direct handling of nutrient flows within the larger food loop shown in Figure 1: agriculture, the food industry, consumers, and waste management. Stakeholders in each of these sectors play a vital role in achieving balanced management of nutrient flows. There are, of course, other important stakeholders such as regulators that can affect nutrient management. However, since these stakeholders often influence actions in more than one sector, their role is discussed below in the section about enabling change, along with institutional structures and regulations.

Agriculture in this context is defined as primary food producers. The food industry includes manufacturers and processors, distributors, and wholesalers. Consumers comprise households and restaurants, as well as local food retailers such as grocery stores which we deem employ similar nutrient-management strategies. The waste-management sector, generally including solid-waste and wastewater-management organizations, is responsible for the collection, treatment, and disposal of solid and liquid wastes. It should be noted that these sectors are dependent on each other and thus management measures are interdependent and linked across sectors.

Waste Hierarchy

The management framework that we formulate in this article is based on the waste hierarchy commonly used in solid-waste management (European Commission, 2008; ARCADIS, 2010). Indeed, variations of the generalized “reduce, reuse, recycle” model are common and the basis of waste management in many countries (Sakai et al. 2011).

1. *Reduce* a) waste generation and b) harmful contents in products
2. *Reuse* the waste more or less as it is
3. *Recycle* the waste as input to new products (including biogas production)
4. *Incinerate*
5. *Dispose*

From a nutrient-management perspective, the above steps are interpreted as follows. Reduction aims at preventing the generation of waste containing nutrients and thus the need to tap mineral nutrient reserves. This includes (Step 1a) reduced volumes and, perhaps more importantly, (Step 1b) minimizing harmful and unwanted contents in products and materials. If the nutrients are not mixed with contaminants, they can be recovered and (Step 2) reused without treatment beyond sanitization (WHO, 2006). If the food-waste material is not safe or not in a state that allows for direct reuse, treatment processes can recycle it into new products (Step 3).

The final two steps of the waste hierarchy are of less interest for purposes of nutrient management since opportunities for nutrient recovery are small. Incineration (Step 4) of food waste is an option, as both the emissions and the ashes contain a variety of plant nutrients, including phosphorus and potassium. However, all carbon and nitrogen are lost and the amount of plant-available phosphorus in ashes is reduced (Zhang et al. 2001). Incineration is therefore mainly used to reduce the volume of solid waste and to recover energy. Finally, the waste hierarchy recommends (Step 5) disposal, most often landfilling, only for material that cannot be used in the previous four steps. We focus on the first three steps as the most effective for improving nutrient management.

Strategy Framework

This article presents a number of functional criteria (Table 1) that may guide technology and policy development within key sectors to improve nutrient management. Criteria selection is a sensitive issue, since it often reflects decision-maker preferences. While aware of this inclination, we carefully developed sustainability criteria through a series of workshops and meetings with a multi-disciplinary group of researchers.[2] The criteria presented here should be at least partially measureable and should guide policy makers and technology developers in system im-

[2] A summary from the initial workshop supported by the SanWatPUA network can be found at http://www.urbanwater.se/sites/default/files/filer/sanwatpua_p-workshop_summary.pdf. The table presented in this article was developed in subsequent meetings and refined through an iterative review process.

Table 1 Functional criterion for improving nutrient management in the food chain. Supporting guidelines and policy documents are shown in Table 2. Arrows indicate direction of material flows.

Key Sectors / Waste strategies	Functional Criteria: Agriculture →	Food Industry →	Consumers →	Waste Management
Step 1: *Source reduction*	+ Increase fertilizer use efficiency + Minimize use of hormones & chemicals + Use no harmful chemicals	+ Minimize food waste within industry + Optimize package size & design for sale to minimize waste + Minimize nutrients in food additives, unless proven health benefits + Use no harmful additives in food or packaging materials	+ Minimize food waste + Minimize meat & dairy consumption + Minimize purchase of products with food additives (without proven health benefits)	+ Minimize dilution/ mixing of waste streams + Minimize harmful chemicals entering waste streams
Step 2: *Maximum reuse of non-processed nutrients*	+ Maximize reuse of food and crop waste for soil improvement or fodder	+ Maximize recovery of food residues from industry for reuse as food/fodder or fertilizer	+ Separation of food waste and reuse at home, whenever feasible and safe + Sort left-over medicines and harmful chemicals in separate waste streams	+ Maximize systems reuse of nutrient-rich waste products
Step 3: *Maximum recycling of processed nutrients*	+ Return recycled food- and crop-waste products to agriculture whenever safe and feasible	+ Recycle non-reused food waste into productive products whenever safe and feasible	+ Maximize purchase of items produced from recycled waste + Recycle food waste at home, whenever feasible and safe + Separate food waste for further processing	+ Recycle non-reused nutrients in waste into productive products whenever safe and feasible

provement. The following sections provide supporting arguments for selecting the functional criteria.

Agriculture

Farmers around the world have typically used locally based food-loop strategies for generations. Optimizing internal recycling of organic material at the farm level should, of course, be encouraged. The criteria presented here focus on what the agriculture sector (primary producers of crops and livestock) can do to enable wider food loops in connection with other stakeholders.

A primary concern is, of course, that agriculture should not become a dumping ground for society's waste. Therefore, the first priority should be efficient use of fertilizers and minimization of hormone and chemical additions to the soil. Use of harmful chemicals, including those in recycled food waste, should be discontinued to avoid long-term contamination of soils. The second priority strategy should be to reuse food waste directly on the farm. This includes using unprocessed urine as fertilizer and giving food waste directly to livestock. Export of manure from areas with abundant livestock to crop-intensive areas is a reuse option that may need wider stakeholder collaboration. It requires dewatering of the manure to achieve the most cost-effective transport, and thus there may be advantages for tighter collaboration with the waste-management sector that regularly uses dewatering technology (UWE, 2013). Finally, food waste that cannot be directly reused should be recycled into fertilizers or fodder whenever safe and feasible.

Maximizing the return of food-related material flows to agriculture in this way, particularly at a local scale, can greatly reduce nutrient losses to water and air, as well as improve soil conditions. However, these strategies require that farmers know about optimal fertilizer and chemical dosing to prevent over-fertilization or accumulation of other toxic compounds. In particular, information about the fertilizing values of potential reused and recycled food wastes needs to be documented and disseminated, as different wastes have different characteristics and thus differ in expected fertilizer effect (Delin et al. 2012). The same applies to using food-waste products as fodder, which can be encouraged through formalization and product marketing to assure quality and content standards. Implementation of these strategies will require guidelines for application of a variety of food-waste products, both those produced directly at the farm and those from other sectors. This should include standardization and reference values for element balances for a variety of nutrients and organic carbon substrates (Öborn et al. 2003). One move in this direction is the quality certification rules for biowaste digestate from the Swedish waste-management authorities, which requires that levels of nitrogen, phosphorus, potassium, magnesium, sulfur, and calcium must be declared (SP, 2013).

Food Industry

The food industry has a critical role to play concerning efficient use of nutrients, particularly food additives, and reducing waste in the food chain. Food industry waste-reduction measures can range from improving transport and handling infrastructure, including better coordination with suppliers and consumers, to increasing the lifespan of food through proper storage and packaging. For example, a recent study in Sweden found that 20–25% of household food waste could be related to packaging that was either difficult to empty or too large (Williams et al. 2012). New packaging standards could reduce food waste, for instance through hydrophobic lining for better emptying of containers or by designing packaging to match consumer eating habits (e.g., avoiding extra-large portions that often spoil).

In addition, improving efficient use of nutrients requires minimizing unnecessary use of food additives. For example, use of phosphorus-containing additives in processed food and animal feed has increased in the last few decades, contributing to the increased demand on mined phosphate. These compounds are used as dietary supplements and for functional purposes such as emulsifiers, stabilizers, or preserving moisture and color. Winger et al. (2012) refer to several studies which estimate that up to 50% of the daily phosphorus intake in affluent countries is from food additives. Medical knowledge has linked higher blood-phosphorus levels to significant health risks, including cardiovascular disease, deterioration of kidney function (e.g., Dhingra et al. 2007), and bone disease (e.g., Sax, 2001). The development trend toward using phytase enzymes in animal feed can significantly reduce the need for phosphorus additions and dietary supplements.[3]

Food additives and packaging material (which contain compounds that may migrate into food) should also be free from toxic and persistent substances because they can make it difficult to later reuse and/or recycle food. Although outside the specific context of food loops, it is, of course, advantageous to minimize the amount of packaging and design it for material recovery. The recovery rate of nutrients in food waste can only be improved if the waste is uncontaminated, with chemical and pathogen concentrations close to or below background levels. For example, some plastic packaging may contaminate the food content by releasing Bisfenol A and phthalates, two hormone-disturbing chemicals linked to a number of diseases (Rudel et al. 2011). Avoidance of such substances in food and packaging would improve public health and facilitate the design of more effective food loops.

The food industry also has the potential to develop internal strategies to maximize recovery of food residues for direct reuse and/or recycling into new products. Mena et al. (2011) identify a number of areas where lack of communication and waste policies cause food waste in the food industry, such as lack of information sharing causing forecasting difficulties and poor ordering, or lack of monitoring routines for measuring waste creation. There are opportunities to realize economic gains by optimizing the efficient use of food resources. For example, slaughterhouses and fish industries can grind bones and sell the meal as fertilizer (Jeng et al. 2006). Additionally, green technologies are increasingly promoted as a means of extracting valuable chemicals from food residues, such as turning citrus waste into limonene (Luque & Clark, 2013).[4]

Consumers

Consumers, including local food retailers, can play a major role in preventing food waste and reducing contamination of nutrient-rich waste streams so that they can more easily be recovered. In industrialized countries, the share of food waste is significantly higher in the consumption phase of the supply chain, estimated to be approximately 95–115 kilograms (kg) per capita/year in Europe and North America compared to 6–11 kg per capita/year in sub-Saharan Africa and South and Southeast Asia (Gustavsson et al. 2011). A recent study estimates that about 40% of household-food waste in the UK is due to cooking and serving more food than can be consumed (Quested & Johnson, 2009). Better planning in food purchasing and creative use of leftovers by households could significantly reduce this volume. In addition, consumers can reduce waste through proper storage, attention to expiration dates, and

[3] Phytase is an enzyme that catalyzes the hydrolysis of indigestible organic phosphorus, releasing usable forms of inorganic phosphorus. Its use in animal feed can enhance the nutritive value of plant material.

[4] Limonene is used in food manufacturing, medicines, cosmetics, insecticides, cleaning products, and solvents.

more careful preparation (e.g., cutting and properly cooking food). Restaurants and caterers can track food frequently left uneaten or sent back by customers and modify the menu based on this information. Reduction of food waste can result in direct economic gains for consumers. Policy measures like the imposition of fees for trash collection and disposal can be effective in reducing consumer waste.

From environmental and nutrient-management perspectives, lower consumption of meat and dairy products would also significantly reduce the need for input of external nutrients into the food loop. For example, a meat-based diet requires approximately three times the phosphorus as a vegetarian diet and results in more nitrogen excreted by humans into the wastewater system (Cordell et al. 2009). Thus, reduction of meat and dairy products in the diet would substantially lower the need for chemical fertilizers.

Consumers can also pave the way for increased nutrient recovery through proper management of household waste. This includes separation of organic waste from other items. Placing left-over medicines and harmful chemicals into separate waste streams, for example, can significantly reduce contaminants in wastewater, making it easier to recycle sludge and water back to agriculture. Similarly, the diversion of fats, oils, and grease from wastewater flows can increase the efficiency of associated systems. Fats can be captured at home or public kitchens and either recycled into composts or collected by the waste sector for processing into biofuels, soaps, and other products.

In addition, consumers can be encouraged to practice reuse and recycling, for example by food donations or composting. There is an increasing trend toward redistribution of surplus from catering and retail sectors to human consumption, largely through soup kitchens and food banks (Alexander & Smaje, 2008). In many countries there are "Good Samaritan" laws that protect donors from liability. Feeding domestic animals with food scraps and leftovers is another option. For example, hog farmers have traditionally relied on food scraps to sustain their livestock and in some areas may provide storage containers and low-cost pick-up service. Of course, consumers need to be aware of what types of scraps are appropriate for animal consumption and sort waste properly. Composting can be done on-site at the household level or off-site, often in collaboration with the waste-management sector.

Consumers can also influence the food loop through their shopping choices by minimizing purchases with unnecessary food additives and increasing consumption of products that contribute to nutrient recovery in the food loop. Informed decisions, however, require knowledge. Information dissemination and proper training in how and why to buy food that is easily recovered will play an important role in mainstreaming these practices.

Waste Management

Waste management is defined here as the collecting, transporting, processing, recycling. or disposing of waste materials (Demirbas, 2011), including solid and liquid wastes from households and industry. The standard has until now been focused on infrastructure for managing linear waste flows, generally from waste production to landfills or incinerators. However, significant volumes of nutrients end up in solid and liquid wastes. The waste-management sector can therefore play a crucial role for improved nutrient recovery and reuse through three important activities: 1) implementing nutrient-focused waste-management systems, especially in urban areas; 2) acting as a watchdog to minimize contaminants in the food loop; and 3) producing nutrient-rich waste products that are acceptable for both farmers and consumers.

To efficiently recycle nutrients, the waste-management sector should minimize the dilution of nutrients and reduce the amount of hazardous chemicals in waste flows. With respect to nutrient-rich waste in urban areas, human excreta is the single largest source (Cordell et al. 2009) followed by food waste (Gustavsson et al. 2011).These nutrients are more easily accessed if they are collected in separate flows not polluted by chemical substances. In the wastewater sector, minimizing excess water (e.g., in-leakage from pipes or stormwater) can significantly reduce treatment costs and simplify the extraction of nutrients. Systems that separate human excreta from other household wastewater (i.e., greywater) are even better from a nutrient-recovery perspective, as the nutrients are then concentrated in smaller volumes and a majority of contaminants are removed with the greywater.

Food wastes should also be considered separately. Today, they are usually mixed with other wastes and either incinerated or landfilled. However, systems do exist when they are separated, as in Sweden, where approximately 60% of municipalities collect food waste to produce the nutrient-rich fertilizer digestate as well as biogas by anaerobic digestion. Experience shows that implementing a well-functioning food-waste collection system for households can take several years, as it requires planning, adequate personnel resources, information, and follow-up (Avfall Sverige, 2013).

Table 2 Supporting guidelines and policy actions that should be developed for improving nutrient management within key sectors based on the waste strategy that they support. Points highlighted in bold will require collaboration across sectors.

Agriculture	*Food Industry*	*Consumers*	*Waste management*
+ Register of safe agricultural fertilizers & chemicals (including those from food waste) + Guidelines for reuse/recycling food waste within agriculture **+ Certification of "reuse" agriculture products**	**+ Vision for food-loop management, including collaboration points and standards for reuse/ recycling** + Register of food additives, including nutrient content, toxicity, persistence, and health effects **+ Certification & product labeling to promote reuse/recycling**	**+ "Sustainable lifestyle" guidelines, including advice on purchasing, preparation, & storage** + Incentives for household-level reuse/recycling of food products **+ Guidelines for home reuse, separation of food waste & safe disposal of harmful chemicals**	+ Technical standards & organizational norms for designing systems for nutrient reuse/recycling **+ Monitoring standards & norms for tracking nutrients and harmful chemicals in waste**

Waste and wastewater utilities are strategically positioned to become watchdogs over harmful waste that can hamper nutrient recovery. The European Union (EU) estimates that some 140,000 substances are currently registered in products (Environment Directorate General, 2007) and very few of them have been properly tested for impact on humans and the environment (although several hundred chemicals are on a watch list). Capture and removal of all such substances from waste flows would be extremely costly, if not technically infeasible. However, waste managers can post warning signals for products that pose a risk to reuse and recycling. They can work closely together with manufacturers, environmental organizations, and chemical agencies in such matters. Manufacturers could be approached from two sides: legal restrictions on use of certain substances and consumer boycotts of household products with unwanted content.

Waste-management agencies can also produce nutrient-rich waste products and thus be key players in creating a viable market. A number of techniques are available to recover nutrients from waste streams; ranging from low-tech solutions, such as direct use of urine, to high-tech extraction of nutrients from municipal wastewater (e.g., struvite production). Transparent management and certification processes, preferably in close dialogue with farmers and consumers, can ensure acceptable and high-quality products. Sweden, for example, has implemented certification of solid waste-derived fertilizers and sewage sludge to reduce discharges of heavy metals and organic pollutants in the raw wastewater, improving the quality of waste-derived fertilizers for agriculture. The waste-management sector should also establish measurable standards and organizational norms that maximize potential for recovery of nutrients from food-derived waste and their return to agriculture.

Policy Strategies

This section provides suggestions for how the criteria presented in Table 1 can be translated into policy (Table 2). Many of the actions suggested here are guidelines, standards, and certification systems, some of which are sector-specific, but several that require input and action from multiple sectors (highlighted in bold in Table 2). For example, a register of safe agricultural fertilizers and chemicals (including those produced from food waste) will require information from other sectors regarding the contents of these products. The information to create many of these guidelines already exists, but needs to be synthesized into more readily accessible platforms.

In the agriculture sector, farmers are primarily concerned about the quality of products applied to their fields (and potential negative consequences) and the potential to sell their produce. They need information regarding the contents of recovered food waste and guidelines on how to best apply these products. To eliminate harmful chemicals in the food loop, a register of safe fertilizers and chemicals for agricultural use should be developed through collaboration of agricultural and food/drug specialists. Finally, quality certification of products from "reuse" agriculture can build consumer acceptance and increase the number of farmers adhering to such practices. Such a certification process would, of course, require collaboration with stakeholders across the entire food loop.

As the food industry comprises a diverse and complex network of actors involved in transporting, processing, packaging, and wholesaling, a unifying vision is needed that outlines a holistic perspective regarding nutrient management, particularly highlighting potential areas for stakeholder collaboration. Such a vision needs to include policy documents and guidelines for minimizing food waste, limiting additives, and recovering food products within the industry. A register of food additives containing information on nutrient content, toxicity, persistence, and health effects would add transparency to negotiations between industry partners and provide consistent information to consumers. An industry "reuse standard" would also strengthen intra-industry cooperation and build consumer acceptance of products with recovered nutrients.

Product labeling by the food industry would also assist consumers to make informed choices, as would "lifestyle guidelines," which include purchasing recommendations, as well as advice on purchasing, preparation, food storage, and home reuse. Further guidelines for home reuse, separation of food waste, and proper disposal of chemicals are also needed. These guidelines could be distributed by a number of different agencies, for example, grocery stores, municipalities, and housing companies. Of course, information dissemination by itself will not significantly change consumer behavior. Incentives are needed to encourage consumer reuse/recycling, including financial incentives/rebates and construction of supportive infrastructure that makes it easy to practice reuse.

As noted earlier, the waste-management sector has a critical watchdog role to play. This role can be strengthened by establishing monitoring standards (locally or nationally) for harmful chemicals in waste flows. In addition, the sector can work to establish technical standards and organizational norms for nutrient reuse/recycling. Standards for sewage sludge recycling, for example, are a step in this direction.

Enabling Change

Achieving the criteria outlined in this article will require large changes in how stakeholders behave and interact. The change required must go beyond policy documents to result in action and ultimately changes in infrastructure and institutions. Numerous crosscutting issues can act as barriers or drivers for change. Many of these issues deal with anchoring the functional criteria within society, legitimizing actions, and monitoring side effects. We identify the following issues, further discussed below, as critical for enabling transitions within the food loop and allowing for implementation of the functional criteria (Storbjörk & Söderberg, 2003; Bergek et al. 2008; Fam & Mitchell, 2013):

- Institutional capacity for system management
- Effective collaboration between sectors
- Supportive legislation
- Transparent system for monitoring and quality control
- Reliable data and evidence-based cost-benefit calculations
- Knowledge and incentives for action

One of the most critical issues is the institutional capacity to manage nutrient flows throughout the entire loop of food production, processing, consumption, waste collection and treatment, and back to the fields. If the entire system is to function properly, a clear division of roles and responsibilities among stakeholders is necessary to assure cooperation and minimize conflict. Although food loops are ideally closed at a local level, institutional support for this work can be established at multiple levels, including internationally. In fact, national and international actors likely have the best capacity to initiate policy strategies and lead collaborative action.

Providing an arena for communication and collaboration among stakeholders at an early stage of policy implementation increases the potential for a well-functioning recovery system, both from an organizational and environmental point of view (Jönsson et al. 2010). A number of the policy actions outlined in Table 2 can act as starting points for establishing the necessary collaboration across sectors. For example, the development of certification systems or "lifestyle guidelines" can bring multiple stakeholders together to work on a concrete task. Cooperation in the development of such specific documents, perhaps facilitated by national or international actors, may pave the way for further collaboration.

A related issue is the need for supportive legislation that encourages nutrient recovery. Today, one of the major stumbling blocks for nutrient reuse and recycling is legislation that directly or indirectly discourages such practices. Waste flows containing nutrients are often regulated under different and sometimes conflicting statutes—water, health, environment and so forth—which makes interpretation of laws difficult for local authorities. Negative perceptions of human excreta also affect regulations. For example, human urine and feces are currently not permitted by EU regulation for organic farming, which means that farmers using them cannot be certified as organic (Johansson & Kvarnström, 2005). This exclusion is considered a cultural construction rather than a scientific distinction. Current legislation needs to be reviewed to ensure that it does not inhibit nutrient reuse/recycling.

In addition, a transparent system for monitoring and quality-control should be developed for mapping nutrient flows and certifying products. Expanding the concept of the phosphorus footprint is one possibility

(Lott et al. 2009; Metson et al. 2012).[5] Such a system would allow for monitoring of quantifiable goals and assure quality of recycled products. Various sectors would have a role, with a need for coordination among monitoring systems. It has been suggested that the waste-management sector be responsible for developing a monitoring system, but specific stakeholders involved will likely be context specific.

A monitoring system needs to be based on reliable data and evidence-based cost-benefit calculations. Calculating accurate costs and benefits requires a system perspective so that nutrient recovery does not lead to excessive energy use or result in substantial increases in the release of greenhouse gases when fulfilling the functional criteria. Thus, it requires a broad data set, some of which is currently missing or under-researched. However, research is ongoing in this field, largely based on substance flow analysis (Cordell et al. 2012), and new data should soon fill in missing pieces.

Many of the functional criteria are dependent on stakeholder knowledge of waste products and their willingness to reduce the use of nutrients and/or increase the use of recovered products. For this to happen, an active information and dissemination program is needed that targets all stakeholders. Of course, the message has to be adapted for each stakeholder group, for example through better fertilizers for farmers and environmental stewardship for consumers. In addition, local conditions, such as population density and environmental awareness are important factors to consider when designing information campaigns.

Finally, economic incentives for all stakeholders are needed. This requires establishing markets for reused/recycled products and calculations of local nutrient costs. An example of a recent initiative to create a market for recycled nutrients as a commodity is the Dutch Phosphate Value Chain Agreement (Nutrient Platform NL), founded in 2011 by the Dutch State Secretary for Infrastructure and the Environment and the national farmers' organization (LTO Nederland). It includes more than 35 Dutch companies, research institutes, governments, and nongovernmental organizations (NGOs) working to create a market for recycled phosphate.[6] Policy development will play a critical role in defining economic incentives, especially since the costs for redesigning systems do not always fall on the same sectors as those receiving the benefits of reuse. Polluter-pays principles or "quality" certification can be effective tools for balancing costs and benefits among sectors.

Conclusion

This article provides vision, criteria, and supporting strategies for improving nutrient management in the food chain. It presents a framework for closed-loop nutrient management based on a multi-stakeholder approach to the waste hierarchy. It outlines the roles of four key sectors (agriculture, food industry, consumers, and waste management) in reducing, reusing, and recycling nutrients within the food loop. The functional criteria outlined in this framework (Table 1) aim at minimizing food waste and harmful chemicals in food and waste products. They also aim to maximize the recovery of nutrients in food waste through reuse and recycling of waste flows. The criteria presented here should be seen as starting points for the development of measureable indicators which can help policy- and decision-makers monitor progress toward improved nutrient efficiency. Effectively closing the loop on nutrient flows will require action by all stakeholders. This article has also highlighted examples of actions that each sector can take and suggested several policy documents that should be developed (Table 2).

A number of positive examples exist of policy aimed at food-waste reduction and recovery. For example, the United States Department of Agriculture (USDA) and the United States Environmental Protection Agency (USEPA) are collaborating on policies to reduce and recover food waste. The United States food waste and recovery challenges invite actors throughout the food chain to disseminate information about best practices and set specific quantitative food-waste goals (mostly related to waste reduction). These challenges may be a good platform for implementing the framework outlined in this article, which could help these programs shift their focus from waste reduction to holistic material flow management and bring onboard the non-consumer sectors that are currently poorly represented. Another positive example is Sweden where the EPA has recommended national goals of returning 40% of phosphorus and 10% of nitrogen from wastewater to agriculture; managing manure so that nutrient additions balance depletion; and treating at least 50% of food waste so that nutrients are recovered (Naturvårdsverket, 2013). As these recommendations are still new (and not yet official), there are few practical guidelines for how to achieve them. Again, the framework in this article may provide guidance.

Implementing the approach outlined in this article will require widespread cooperation and possibly new organizational structures. However, concerns

[5] The phosphorus footprint is a calculation of the average amount of mined phosphorus required to produce the food consumed per capita per annum.

[6] See http://www.nutrient platform.org.

about food security and the need for more sustainable management of nutrients may provide a common cause for uniting diverse stakeholders. It is our hope that the criteria and suggested policy actions can serve as points of departure for local champions to initiate the necessary dialogue. Stakeholders need to agree on a common vision. The one presented here may provide a starting point. Closing the food loop is possible if all stakeholders apply thinking from the waste hierarchy, minimizing waste within their own sector and assuring that waste flows to other sectors are in optimal condition for reuse. No sector can do it alone, but together we can achieve sustainable nutrient management.

References

Alexander, C. & Smaje, C. 2008. Surplus retail food redistribution: an analysis of a third sector model. *Resources, Conservation, and Recycling* 52(11):1290–1298.

ARCADIS. 2010. *Analysis of the Evolution of Waste Reduction and the Scope of Waste Prevention*. Final Report ENV.G.4/FRA/2008/0112. Deurne, Belgium: ARCADIS Belgium.

Avfall Sverige. 2013. *Swedish Waste Management*. Stockholm, Sweden Avfall Sverige AB.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. 2008. Analyzing the functional dynamics of technological innovation systems : a scheme of analysis. *Research Policy* 37(3):407–429.

Chen, X.-P., Cui, Z.-L., Vitousek, P., Cassman, K., Matson, P., Bai, J.-S., Meng, Q.-F., Hou, P., Yue, S.-C., Römheld, V., & Zhang, F.-S. 2011. Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America* 108(16):6399–6404.

Cordell, D., Drangert, J.-O., & White, S. 2009. The story of phosphorus: global food security and food for thought. *Global Environmental Change* 19(2):292–305.

Cordell, D., Neset, T.-S., & Prior, T. 2012. The phosphorus mass balance: identifying "hotspots" in the food system as a roadmap to phosphorus security. *Current Opinion in Biotechnology* 23(6):839–845.

Delin, S., Stenberg, B., Nyberg, A., & Brohede, L. 2012. Potential methods for estimating nitrogen fertilizer value of organic residues. *Soil Use and Management* 28(3):283–291.

Demirbas, A. 2011. Waste management, waste resource facilities and waste conversion processes. *Energy Conversion and Management* 52(2):1280–1287.

Dhingra, R., Sullivan, L., Fox, C., Wang, T., D'Agostino, R., Gaziano, J., & Vasan, R. 2007. Relations of serum phosphorus and calcium levels to the incidence of cardiovascular disease in the community. *Archives of Internal Medicine* 167(9):879–885.

Dordas, C. 2009. Role of nutrients in controlling plant diseases in sustainable agriculture: a review. *Agronomy for Sustainable Development* 28(1):33–46.

Environment Directorate General. 2007. *REACH in Brief*. Brussels: European Commission.

European Commission. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union* 58:3–30.

Fam, D. & Mitchell, C. 2013. Sustainable innovation in wastewater management: lessons for nutrient recovery and reuse. *Local Environment* 18(7):769–780.

Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., Johnston, M., Mueller, N., O'Connell, C., Ray, D., West, P., Balzer, C., Bennett, E., Carpenter, S., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. 2011. Solutions for a cultivated planet. *Nature* 478(7369):337–342.

Godfray, H., Beddington, J., Crute, I., Haddad, L., Lawrence, D., Muir, J., Pretty, J., Robinson, S., Thomas, S., & Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327(5967):812–818.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. 2011. *Global Food Losses and Food Waste*. Rome: UNFAO.

Jeng, A., Haraldsen, T., Grønlund, A., & Pedersen, P. 2006. Meat and bone meal as nitrogen and phosphorus fertilizer to cereals and rye grass. *Nutrient Cycling in Agroecosystems* 76(2): 183–191.

Johansson, M. & Kvarnström, E. 2005. *A Review of Sanitation Regulatory Frameworks*. Stockholm: EcoSanRes Programme.

Jönsson, H., Tidåker, P., & Stintzing, A. 2010. Role of farmers in improving the sustainability of sanitation systems. In B. Van Vliet (Ed.), *Social Perspectives of the Sanitation Challenge*. pp. 179–188. Dordrecht: Springer.

Lal, R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development* 17(2):197–209.

Lott, J., Bojarski, M., Kolasa, J., Batten, G., & Campbell, L. 2009. A review of the phosphorus content of dry cereal and legume crops of the world. *International Journal of Agricultural Resources, Governance, and Ecology* 8(5/6):351–370.

Luque, R. & Clark, J. 2013. Valorisation of food residues: waste to wealth using green chemical technologies. *Sustainable Chemical Processes* 1(1):10.

Mena, C., Adenso-Diaz, B., & Yurt, O. 2011. The causes of food waste in the supplier–retailer interface: evidences from the UK and Spain. *Resources, Conservation, and Recycling* 55 (6):648–658.

Metson, G., Bennett, E., & Elser, J. 2012. The role of diet in phosphorus demand. *Environmental Research Letters* 7(4): 044043.

Naturvårdsverket. 2013. *Hållbar återföring av fosfor Naturvårdverkets redovisning av ett uppdrag från regeringen (Sustainable phosphorus recycling Environmental Protection Agency's reporting of a commission from the government).* Stockholm: Swedish Environmental Protection Agency.

Öborn, I., Edwards, A., Witter, E., Oenema, O., Ivarsson, K., Withers, P., Nilsson, S., & Richert Stinzing, A. 2003. Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. *European Journal of Agronomy* 20(1):211–225.

Price, J. & Joseph, J. 2000. Demand management—a basis for waste policy: A critical review of the applicability of the waste hierarchy in terms of achieving sustainable waste management. *Sustainable Development* 8(2):96–105.

Quested, T. & Johnson, H. 2009. *Household Food and Drink Waste in the UK*. Banbury: WRAP.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., de Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., & Foley, J. 2009. A safe operating space for humanity. *Nature* 461(7263):472–475.

Rudel, R., Gray, J., Engel, C., Rawsthorne, T., Dodson, R., Ackerman, J., Rizzo, J., Nudelman, J., & Brody, J. 2011. Food packaging and bisphenol A and bis(2-ethyhexyl) phthalate exposure: findings from a dietary intervention. *Environmental Health Perspectives* 119(7):914–920.

Sakai, S., Yoshida, H., Hirai, Y., Asari, M., Takigami, H., Takahashi, S., Tomoda, K., Peeler, M., Wejchert, J., Unterseh, T., Douvan, A., Hathaway, R., Hylander, L., Fischer, C., Oh, G., Jinhui, L., & Chi, N. 2011. International comparitive study of 3R and waste management policy development. *Journal of Material Cycles and Waste Manangement* 13(2):86–102.

Sax, L. 2001. The Institute of Medicine's "dietary reference intake" for phosphorus: a critical perspective. *Journal of the American College of Nutrition* 20(4):271–278.

SP Technical Research Institute of Sweden (SP). 2013. *Certifieringsregler för Biogödsel (Rules for Certification of Digestate).* SPCR 120. Borås, Sweden: Avfall Sverige.

Storbjörk, S. & Söderberg, H. 2003. *Plötsligt Händer det: Institutionella Förutsättningar för Uthålliga VA-System* (*Suddenly It Happens: Institutional Requirements For a Sustainable Wastewater System*). Urban Water Report 2003:1. Göteborg: Chalmers University of Technology.

Tidåker, P., Sjöberg, C., & Jönsson, H. 2007. Local recycling of plant nutrients from small-scale wastewater systems to farmland: a Swedish scenario study. *Resources, Conservation, and Recycling* 49(4):388–405.

University of the West of England (UWE). 2013. *Science for Environment Policy In-depth Report: Sustainable Phosphorus Use.* Bristol: UWE.

World Health Organization (WHO). 2006. *Guidelines for the Safe Use of Wastewater, Excreta and Greywater: Volume 1 (Policy and Regulatory Aspects).* Geneva: WHO.

Williams, H., Wikström, F., Otterbring, T., Löfgren, M., & Gustafsson, A. 2012. Reasons for household food waste with special attention to packaging. *Journal of Cleaner Production* 24:141–148.

Winger, R., Uribarri, J., & Lloyd, L. 2012. Phosphorus-containing food additives: an insidious danger for people with chronic kidney disease. *Trends in Food Science & Technology* 24(2): 92–102.

Zhang, F., Yamasaki, S., & Nanzyo, M. 2001. Application of waste ashes to agricultural land: effect of incineration temperature on chemical characteristics. *Science of the Total Environment* 264(3):205–214.