Oikos **OIK-02291**

Cease A., Capps K. A., Gates, K. K., McCrackin, M. L., Nidzgorski, D. A. 2015. Consumer- driven nutrient dynamics in in urban environments: The stoichiometry of diet and waste management – Oikos doi: 10.1111/oik.02391

Appendix 1

Calculating human diet patterns

Table A1. File: **Table_A1.pdf.** Consumption of major food staples by region/country and contribution of animal protein to total protein consumption estimated from food availability data (FAOSTAT 2011). Regional categories are defined by FAOSTAT.

Table A2. File: **Table_A2.csv.** Nutrient content of U.S. food groups from the U.S. Department of Agriculture National Nutrient Database for Standard Reference (ABBREV; USDA 2013).

Table A3. **Files: Table_A3.1–A3.12.csv**. Selected nutrient contents of U.S. food groups from the abridged USDA National Nutrient Database (USDA 2013; columns A–F) and calculations of N and P (columns G–I) sorted by food group. Table A3 contains sub-tables as follows: A3.1 Master list summary of nitrogen (N) content, phosphorus (P) content, carbohydrate content, and N:P ratio for each food group; A3.2 Beef; A3.3 Cereals/Grains/Pasta, A3.4 Dairy/Eggs; A3.5 Finfish/Shellfish; A3.6 Lamb/Veal/Game; A3.7 Legumes; A3.8 Nuts/Seeds; A3.9 Pork; A3.10 Poultry; A3.11 Vegetables; and A3.12 Fruits.

Table A4. File: **Table_A4.csv**. Summary of raw values of nitrogen (N), phosphorus (P), and N:P ratio for each diet type.

Table A5. Files: **Table A5.1–A5.5.csv**. Calculation of US omnivore diet, US vegetarian diet, and total diet study P-content. Table A5 contains sub-tables as follows; A5.1 FDA total diet study (TDS) 2003 food consumption results by age and with total US average consumption used to calculate US omnivore and vegetarian diet; A5.2 Calculation of US omnivore diet combining FDA total diet study data with USDA Nutrient Database data (USDA 2013); A5.3 Calculation of US lacto–ovo vegetarian (LOV) diet combining FDA total diet study data with USDA Nutrient Database data; A5.4 Conversion of US omnivore to US vegetarian diet detailing vegetarian substitutes for foods containing meat in the US omnivore diet; A5.5 Estimation of P values from the TDS market basket survey for comparison with our US omnivore diet.

Table A6. File: **Table_A6.pdf.** N and P biomass accumulation calculations.

We assumed that rates of N and P excretion match rates of N and P intake. However, this only holds strictly true when people are neither gaining nor losing mass and human populations are not likely to be in perfect steady state. Therefore, we quantified potential sources of error due to this assumption. Because our analysis focused on annual estimates, we do not account for long-term demographic changes such as increasing or decreasing population size, or mortality and replacement. We estimated the amount of N and P accumulated in human biomass each year due to 1) adult weight gain, and 2) growth of youths. Both of these would cause N- and P-excretion rates to be lower than N and P intake rates. For this exercise, with the goal of assessing the potential error due to assuming steady state, we focused on the United States where all necessary data are readily available.

The average weight for adults 20–74 years old in the United States increased by 0.3 kg year^{-1} between 1960 and 2002 (Ogden 2004). To convert this to N- and P-accumulation, we used data from Forbes and coauthors (1953) on the composition of various human body tissues (Table B1). Since no data are available to allocate adult weight gain among different tissues, we calculated two scenarios: one where all weight gain is from increased striated (skeletal) muscle, which has relatively high N and P concentrations, and one where all weight gain is from increased adipose tissue (fat), which has relatively low N and P concentrations. (The average composition of the entire adult body is not appropriate for these calculations; for example, whole-body %P is six times that of striated muscle because bones are extremely P-rich, but an adult gaining 0.3 kg is unlikely to gain substantial bone mass in the process.) Gaining 0.3 kg year^{-1} of striated muscle would accumulate 0.01 kg N year^{-1} and 0.0005 kg P year^{-1}, and gaining 0.3 kg year^{-1} of adipose tissue would accumulate 0.003 kg N year^{-1} and 0.0001 kg P year^{-1}. Comparing these rates to annual dietary N and P intake under our "US omnivore" diet pattern, the N and P accumulated in striated muscle would be equal to 0.3% of N intake and 0.1% of P intake, and the N and P accumulated in adipose tissue would be equal to 0.07% of N intake and 0.02% of P intake.

To estimate the rates of N- and P-accumulation in the growing bodies of youths, we first calculated an average growth rate across the first 20 years of life. While growth rate changes substantially across childhood and adolescence, this approach provides a simple estimate to assess our population-level analyses, particularly in societies like the United States that have similar numbers of children in each age class (Howden 2011). Ogden and coauthors report that in 2002, 20–29 year old females had an average weight of 64.4 kg, and males of the same age had an average weight of 78.4 kg. Assuming a 1:1 sex ratio, this translates to an average annual growth rate of 3.6 kg year^{-1}. Using whole-body N- and P-concentrations (Forbes 1953, Table B1), we estimate that growing youths accumulate an average of 0.1 kg N year^{-1} and 0.03 kg P year^{-1}. In the US, where 27% of the population is under age 20 (Howden 2011), growing youths accumulate 0.7% of overall dietary N intake, and 2.1% of overall dietary P intake (again using intake rates from our "US omnivore" diet pattern).

Compared with total dietary intake, N- and P-accumulation in the US due to adult weight gain plus growing youths is small (1–2%). We chose not to decrease our estimates of human excretion because other sources of uncertainty in our analyses are much larger, especially in our estimates for developing nations.

References

FAOSTAT 2011. Statistical database food balance sheets. – Food and Agricultural Organization of the United Nations.

Forbes, R. M. et al. 1953. The chemical composition of the adult human body as determined by chemical analysis. – J. Biol. Chem .203: 359–366.

FDA (U.S. Food and Drug Administration). 2003. Total diet study. <www.fda.gov/Food/FoodScienceResearch/TotalDietStudy/default.htm>, accessed 1 July 2014.

Howden, L. M. and Meyer, J. A. 2010. Age and sex composition: 2010. – US Census Bureau.

Ogden, C. L. et al. 2004. Mean body weight, height, and body mass index, United States 1960–2002. Advance data from vital and health statistics; no 347. – National Center for Health Statistics, Hyattsville, MD.

USDA (U.S. Department of Agriculture). 2013. USDA National Nutrient Database for Standard Reference, Release 26. Agricultural Research Service, <www.ars.usda.gov/nutrientdata>, accessed July 2014.

Appendix 2

Files: Figure_A1_-_model_schematic.png

Table_A7.pdf

Table_A8.csv

Table_A9.csv

Calculating waste management patterns

We developed and parameterized a model that tracks nitrogen (N) and phosphorus (P) fluxes from human excreta, through various transformations in waste streams, to their eventual fates as pollution, nutrient storage, or recycling. Figure A1 illustrates the structure of the model. Each node within the waste stream where fluxes split is parameterized as proportions of the incoming flux assigned to each outgoing flux pathway; we assumed that these proportions are constant and do not vary based on the magnitude of the incoming flux.

Flux arrows in Fig. A1 are color-coded according to their effects on the stoichiometry of waste. Solid grey flux arrows indicate places where waste stoichiometry does not change, and where some of the incoming material is assigned to different pathways without biogeochemical transformations. In these cases, a single parameter is applied to both N and P in the model. For example, if a WWTP sends some of its solids to land application and some to landfill, the N:P ratio of the solids is the same in either case. In contrast, checkered blue flux arrows indicate places where waste stoichiometry changes as materials undergo biogeochemical transformations. In these cases, separate parameters are applied to N and P. For example, different proportions of N and P are removed during processing in the WWTP; therefore, the resultant pathways of solids, effluent, and gases have very different N:P ratios from one another and from the untreated sewage.

We wrote an R script (ver. 3.0.2, R Core Development Team 2013) that calculates the kg N and P capita^{-1} year^{-1} at each point in the waste stream for a given input of human excreta. The model also takes as input a comma-separated values (.csv) file with parameters for one or more waste-management patterns (each row in the .csv file is one waste-management pattern) and simultaneously calculates the outputs for all waste-management patterns (as different rows in the output .csv file). The R script is published as Appendix 3.

For each waste pattern described in the Methods, we developed a complete set of parameters covering each flux arrow in Fig. A1. Table A7 is a list of all parameters and the origin and destination nodes in Fig. A1 that they connect in the waste stream. The table also contains the variable names used in the R script for each parameter. Table A8 lists the parameter values for each of the six waste-management patterns and the sources we used to identify those parameters. In addition, some parameter calculations and assumptions are described in more detail below.

Nutrient removal pathways by WWTPs

Primary treatment removes 10% of sewage N and P, secondary treatment and removes 35% of N and 45% of P and tertiary treatment removes 80% of N and 90% of P (USEPA 2008, Van Drecht et al. 2009) (Table A9). Because P does not have a gaseous form, the fraction removed is in the form of solids and the balance is in liquid effluent. Secondary and tertiary treatment remove N either in the form of sewage solids or by the microbial conversion to gaseous forms (N_2 or N_2O). We assigned the N removed by secondary treatment to 30% to solids and 5% to gases because secondary treatment facilities are generally designed to remove nutrients in solid form, although denitrification can occur (Ahn 2006). For tertiary waste treatment, we assumed that 20% of N is removed in solid form and 60% in gaseous forms based on N budgets developed for Toronto and Paris (Forkes 2007, Svirejeva-Hopkins et al. 2013) (sums to 80% N removal as in Van Drecht et al. 2009).

Nitrogen removed by secondary or tertiary treatment as gases can be in the form of N_2 or N_2O. The USEPA estimates that 3.2 g N_2O is produced per person each year at domestic WWTPs (Scheehle and Doorn 2001). We estimate that < 0.1% of N in excrement results in N_2O (calculated as 3.2 g N_2O per person per year divided by 4 kg N in excrement per person per year for the US omnivore diet). We assigned all gaseous N to N_2 because the fraction of N removed from waste as

N_2O at WWTPs is negligible and because our primary interest is waste treatment effects on water pollution.

Similarly, the incineration of WWTP solids produces both N_2 and N_2O. Although N_2O emissions are monitored as part of incinerator permit requirements, much of this N comes from atmospheric N and no data are available to quantify the proportion of dietary N converted to N_2O. We again assigned all incinerated N to N_2; all incinerated P is retained in incinerator ash and landfilled.

Septic systems and latrines

Proper maintenance of decentralized waste treatment systems (septic systems and latrines) includes the periodic (every few years) removal of solids, which are transported to a WWTP, land-applied, or dumped/discharged (usually illegally) to areas such as ditches or surface waters (Moersid 1998). We assumed that solids removed from septic systems and latrines are disposed of in the same manners and proportions, and did not parameterize them separately.

For the US average waste-management pattern, a survey of state agencies responsible for biosolids found that, if known, disposal methods for septic solids included land application (2–85% of septage across responding states), disposal at WWTPs (10–100%), or disposal in a sewage lagoon (0–65%) (NEBRA 2007). Given the wide range of disposal practices across states, for the US average we assigned half of septic solids to land application and half to WWTPs (Table A8).

Some N and P in septic and latrine effluent are attenuated in the soil beneath the drainfield by denitrification, biological uptake, or soil adsorption, and the remainder leaches into groundwater. Attenuation rates differ greatly depending on soil types, seasonal water tables, and other biophysical factors. Nitrogen attenuation is variable (20–80%) and depends on soil conditions that favor denitrification. If septic systems are properly installed and maintained, P retention nears 100% but under suboptimal conditions, attenuation falls to 10–30% (Withers et al. 2014). We were unable to locate studies that quantified average N and P attenuation rates for septic systems. We assigned greater attention of P in septic effluent (75%) than to N (50%) because P adsorbs more strongly in soils than N (especially NO_3^{-1}) (Table A8). Latrines are likely to have lower soil attenuation rates than septic systems, since the nutrients are concentrated in a small area immediately beneath the latrine rather than spread over a larger septic drainfield area, but we were unable to find any studies that have quantified N and P attenuation beneath latrines. As a result, we used the same attenuation parameters for both septic and latrine effluent.

Use of waste treatment facilities in Jakarta and rural Indonesia

The WHO/UNICEF (2008) reports country-level data for the portions of urban and rural Indonesian populations covered by improved sanitation (piped sewer systems, septic systems, pit latrines), shared sanitation (otherwise improved but used by more than one household, unimproved sanitation (bucket, hanging toilet) and open defecation. For rural Indonesia, 39% of the population practices open defecation, and 61% use improved, shared or unimproved facilities, which we assigned to pit latrines (Table A8)

We assume that urban Indonesia data per the WHO/UNICEF report is representative of Jakarta. Accordingly, for the 75% of the population with access to improved and shared sanitation facilities, we assigned 3% to primary WWTPs (Corcoran et al. 2010) and the balance (72%) to septic systems, because a study of Jakarta reported this to be a common practice (Moersid 1998). We classified the remaining 25% as having no access to WWTPs (Table A8)

References

Ahn, Y.-H. 2006. Sustainable nitrogen elimination biotechnologies: a review. – Process Biochemistry 41: 1709–1721.

Corcoran, E. et al. 2010. Sick water? The central role of wastewater management in sustainable development. A rapid response assessment. – UN Environment Programme, UN-HABITAT, GRID-Arendal.

Forkes, J. 2007. Nitrogen balance for the urban food metabolism of Toronto, Canada. – Resourc. Conserv. Recycling 52: 74–94.

Moersid, M. M. 1998. Enhancing the maintenance of septic systems: case study of septic tank maintenance in Jakarta, Indonesia. – Dept of Urban Studies and Planning, Massachusetts Inst. of Technology.

NEBRA 2007. A national biosolids regulation, quality, end use, and disposal survey. – North East Biosolids and Residuals Association, Tamworth, NH, USA.

Scheehle, E. A. and Doorn, M. R. 2001. Improvements to the US wastewater methane and nitrous oxide emissions estimates. Proc. 12th Int. Emission Inventory Conf., Emission Inventories–Applying New Technologies, San Diego, CA, April 2001.

Svirejeva-Hopkins, A. et al. 2013. Nitrogen flows and fates in urban landscapes. – In: Sutton, M. A. et al. (eds), The European nitrogen assessment. Cambridge Univ. Press.

USEPA 2008. Clean watersheds needs survey: 2008 Report to Congress. EPA-832-R-10-002. – Office of Water, Washington, D. C.

Van Drecht, G. et al. 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. – Global Biogeochem. Cycle 23: doi:10.1029/2009GB003458.

Withers, P. J. A. et al. 2014. Do septic tank systems pose a hidden threat to water quality? – Front. Ecol. Environ. 12: 123–130.

Appendix 3

R code for diet and waste management model, as described in Appendix 2.

File: R_code_for_model.R