Towards sustainable and regenerative territories: ecological restructuring of phosphorus retention and mobilization based on substance flow analysis (sfa) in Quirino Province

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Abstract. Phosphorus (P) is an essential and finite nutrient element that cannot be substituted by any other substance. To overcome limited supply of mineral Phosphate rocks (PR) deposits and to contribute to its sustainable management, a better knowledge on P flows is needed. In this study, a Substance Flow Analysis (SFA) for P was conducted for the Quirino Province. Different subsystems were investigated such as forestry, agriculture, anthropogenic consumption, organic wastes, and wastewater management. The researcher found that within the system under study, there is an excess total P inflow into the three (3) major river watersheds system in Quirino Province. The aim of the study was to analyze the flow of Phosphorus that enter, transform, pass through, and leave the territorial subsystems in order to create a knowledge bank that will aid in the transition of Quirino Province from linear to circular metabolism.

Keywords: substance flow analysis, circular economy, phosphorus recycling

1. Introduction
The phosphorus fertilizers that our farmers use today in food production came from mining of phosphorite, or phosphate rock. Estimates show that Earth’s crust contains a total of 65 Million Metric tons phosphate rocks, of which are concentrated to Morocco and Western Sahara. This figure, however, only covers the phosphate rocks that are “sufficiently rich in phosphorus for conversion to useful products by present methods” (Britannica, 2019).

For commercial purposes, phosphate rocks are acidized to form water-soluble phosphorus compounds which are essential additions to fertilizer. The concern is that “phosphorus is wasted on its journey from mining to being eaten by humans, and the wasted phosphorus ends up in waterways where it can cause algal blooms.” (Britannica, 2019). With increasing population, comes increasing demands for food. And increasing food production requires fertilizers for more crop yield. Increased phosphorus usage will deplete the nonrenewable supply of phosphate rock. In fact, researches [1][2][3][4] have shown that the global reserves of phosphate rocks will be depleted in the next 50-100 years. Phosphorus, being faced with lot of challenges in geographic constraints, phosphorus-induced water pollution, increasing usage as nonrenewable resource, calls for sustainable management [5].

According to Nest and Cordell, increasing the efficiency and management of phosphorus can minimize the adverse effects of eutrophication, chemical pollution, climate change and etc. Further, “flow analyses’ have proven to be a valuable tool” in assessing the efficiency of
flow of materials and/or energy [6]. In article written by Weinstock entitled “The Metabolism of a City: The Mathematics of Networks and Urban Surfaces”, cities “are not arrays of material structures, but are regarded as analogous to living beings, as they consume energy, food, water and other materials, excrete wastes and maintain themselves down through the generations.” He also added that metabolism can be related to cities through networks and scaling phenomena. Meaning, mathematically, the cities can be networks of metabolic processes: Rates of resource consumption can be measured through mathematical parameters. Movement of resources within a city is like that of movement of nutrients in the circulatory system of a living thing. This field of study is under industrial ecology and it is called “Urban Metabolism.” However, in an article written by Yan Zhang, the existing multi-scale studies about urban metabolism have been primarily theoretical. Zhang expounded that “application of this particular research to actual planning has been rare.” [7].

What this research is trying to achieve is providing a framework and research model that can be replicated in a local setting to improve nutrient management at macro level. By proving interventions and recommendations in sustainable management of phosphorus, the theme if this research is adhering to the United Nations Sustainable Development Goals of Circular Economy. In connection, this research aims to fill in the gap of urban metabolism research and actual planning in rural territory by providing an extensive knowledge base about the phosphorus metabolism of a territory.

2. Methodology
The methodology came from the set of the literature reviewed: The general approach of this paper was adapted from [7]; the research tactics and more detailed versions of crude phosphorus metabolism model were derived from other literatures reviewed [8][9][10][11][12]. The general approach of the study was illustrated below (Figure 1).

![Figure 1 Research framework adapted from Zhang Y. urban metabolism](image)

The first step, the process analysis, focused on the identifying the different actors within a metabolism. By identifying the possible linear input and output processes and uniting it to produce model of a network that revealed the system’s inner details [7]. For second step, the accounting, Substance Flow Analysis (SFA), one of the research models of Material Flow Analysis (MFA) that focuses on quantifying the flow of a given substance across a region, has been employed in this phosphorus metabolism analysis. This tactic provided approximations of the following: (i) inflows, phosphorus that are entering the system/subsystems/metabolic actors through a particular material in a given time; (ii) inflows, phosphorus that are exiting the system/subsystems/metabolic actors through a particular material in a given time; and (iii) stock, the difference between the total inflows and total outflows in a particular system/subsystems/metabolic actor. However, some P flows were neglected, due to their statistic were not available, and/or not clearly traceable.

The third step was simulation model, which refers to the representation of the dynamics
and system’s internal operating mechanisms that shows metabolic processes and factors that influence them [7]. In this study, ecological dynamics modelling was used through comprehensive Sankey diagram to show how the phosphorus was metabolized in different social, economic, and natural elements of the system.

For the last step, optimization and regulation encompassed the identification of factors that drives the (in)efficiency of metabolic processes and minimizes the environmental impacts. However, this study will only cover the first three steps as the main objective of this paper was to provide knowledge base about the current phosphorus metabolism of Quirino Province.

2.1 System boundary and temporal scale
The system boundary was defined as the administrative border of the Quirino Province (Figure 2). The metes and bounds used were from the Provincial Development and Physical Framework Plan (PDPFP) 2011-2030, which was complemented by map of National Mapping and Resource Information Authority (NAMRIA).

![Figure 2 Administrative map Quirino Province](image)

In addition to that, this study was carried out a static substance flow analysis. Meaning, all the datasets that have been considered and phosphorus flows have been computed were only good a specific year. For the temporal scale, the year 2018 was selected because it provided the researcher the latest and the greatest number of statistical data available for secondary data research. Moreover, a static SFA was made due to the limitation of time and logistics. In the events wherein there was no data available for 2018, the previous or following year/s was referenced.

2.2 Data collection
In this type of analysis, there are two types of data required: material mass flows and P concentration. In this study, the material mass flows datasets were called and under the umbrella term parameters. Material mass flows pertains to values and data which characterizes the amount of raw materials, goods, and products circulating within the territorial system. There were also indicators of the different societal factors of the territory, such as production values, land area, human and animal population, which were included in the parameters. Ergo, these are the values which were gathered by the government statistics offices and other census-concerning agencies.

In general, the parameters were multiplied with their phosphorus concentration values to obtain the elemental form of phosphorus. However, not all P flows were easily determined
by just multiplying the mass flows with its corresponding P concentration value/s: Instead, supplemental equations were employed to obtain the P values (in kg). Shown below are the three (3) general equations, which were adapted from [11], used in the SFA.

The complete list of all parameters and coefficients used in this study is in the supplementary data, Table 2 and 3, respectively.

**Fixed flow equations:**

\[ F_i = P_a \times C_a \]  \( i \) (1)

\( F_i \) is a P flow from one subsystem to another, \( P_a \) is a parameter, and \( C_a \) is a phosphorus coefficient. Example of this Flow 12 (\( F_{12} \)) that shows the wind erosion from croplands to atmosphere.

**Dependent flow equations:**

\[ F_i = F_x \times P_x \]  \( i \) (2)

This type of equations shows how one P flow is dependent on another flow. The Flow 16 (\( F_{16} \)) shows how the P content of post-harvest residues is dependent on the crop production.

**Balancing equations:**

\[ \sum F_{input} = \sum F_{output} \]  \( 3 \)

Balancing equations adheres to the Law of Mass Conservation. Some unknown P flows can be obtained by subtracting the unknown P flow to the overall inflow or export flow. The Flow 83 (\( F_{83} \)) shows how the estimation of remains of wild animals in the forest vis-à-vis to their foraging. The complete list of all parameters and coefficients used in this study is in the supplementary data, Table 2 and 3, respectively.

3. **Results and discussion**

To effectively visualize the findings of the phosphorus metabolism of the whole Province of Quirino, a Sankey diagram was formulated based on the information of Table 1. Shown below is the Figure 3, which contains the 82 simulated P flows that entered, exited, transformed through the total of 20 metabolic actors of five (5) subsystems of the Quirino Province system. The width of each arrow was directly proportional to the quantity of the phosphorus per flow: The thicker the arrow, the greater the value. Each flow (\( F \)) can be referenced back to the Table 1 of Supplementary Data.

3.1 **Province of Quirino (main system)**

The total P that circulated within the Quirino Province for 2018 was 75 669 018.49 kg-P. Based on Table 3, the largest P flows came from \( F_{34} \) and \( F_{37} \) which represented the Forest uptake, and Forest residues, respectively. These flows were heavily dependent on the published values of above-ground biomass densities of tropical forests, and average Carbon-Phosphorus uptake ratio in tropical ecosystems. The magnitude of these forest P flows relatively to the whole system went beyond the researcher’s expectations because the hypothesis and goal setting were geared towards built-up areas and agriculture.\(^1\)

\(^1\) (Note for the following illustrations of Sankey Diagrams: The width of the arrows does not represent the actual value of phosphorus (kg-P) but it represents the amount of P in each flow in relation to the whole system (% of total P) with a scale of 1%:0.15 cm:28pt (A1 size). Percentage values amounting to 2% and/or lower had a default width of 0.25pt for ease of visualization. High-resolution versions of the following diagrams are in the Supplementary Information)
3.2 Forestry

The present analysis revealed that in 2018, Forestry subsystem had elevated outflows ($\Delta = -14217.34 \text{ MT-P}$) associated with immense flow from $F_{34}$: Erosion and runoff from grassland, accounting 95.75% of total P outflows of the subsystem (14 403.32 MT-P). Following this is a mass flow from $F_{24}$: Forest trees uptake, and $F_{25}$: Forest residues (20.4259%) which was mainly due to nutrient cycling of the forest and forestlands.

Based on the data gathered, the main concern was on the subsystem of grasslands due to erosion and runoff. The grasslands possess high negative delta (-13798.70 MT-P). There is a huge loss of nutrients over time, mainly due to surface runoffs and erosion, and subsurface runoff and nutrient leaching. Grasslands is the leading landcover which is losing P through surface runoff and soil erosion (13 791.29 MT-P/year). This thesis referenced the works of local scientists--Francisco, H., & delos Angeles, M. According to their report, it is recorded that in the Philippines, grasslands / pasturelands records an estimated annual soil loss amounting to 267 tons per hectare ($P_{234}$).

**Figure 3** Comprehensive sankey diagram of phosphorus metabolism in Province of Quirino for 2018

**Figure 4** Sankey diagram of phosphorus metabolism in forestry subsystem of Province of Quirino for 2018
3.3 Agriculture
Of the eight (8) Phosphorus inflows of the agricultural subsystem, F₆₄: Mineral fertilizer consumption and F₆₅: Feed additive consumption were the two largest inflows, with the total of 97.47% of P inflow value of 2843.93 MT-P. F₆₄ had a 61.08% share in inflows, while by F₆₅ had a total inflow of 36.39%.

Moreover, four (4) out of five (5) metabolic actors in this subsystem indicated an apparent phosphorus accumulation: in the year 2018, crop residues accumulated a total of 2941.20 MT-P, making it the biggest “gainer” in the subsystem. Additionally, manure was comprised of 866.89 MT-P. The accumulation in these two metabolic actors were products of F₆₆: Post-harvest residues for the crop residues, and F₆₇: Livestock and poultry excreta for the manure. Along with these, Livestock (Δ = +8.30) and Crops (Δ = +295.11) were also considered as “gainers”. Nonetheless, the overall change in balance remains negative (Δ = -6042.56) due to a phosphorus depletion of 10129.93 MT-P in the croplands.

The biggest contributor to the outflows in the agriculture subsystem was F₆₈: Erosion and runoff from croplands, consisted of 7775.89 MT-P or 87.5% of total outflows. It was then followed by F₆₉: Wind erosion from croplands.

![Sankey diagram of phosphorus metabolism in agriculture subsystem of Province of Quirino for 2018](image)

**Figure 5** Sankey diagram of phosphorus metabolism in agriculture subsystem of Province of Quirino for 2018

3.4 Retailing
An assumption that there were no storage facilities available for products was made in this subsystem—however, to avoid generalization, each variable was examined. For instance, under the livestock and poultry group, eight (8) commodities were included. The production of each commodity—such as chicken eggs, was subtracted by the rural and urban population consumption. If the resulting value is negative, it indicates a negative supply—imports. Contrary, if the equation returns a positive value, then there is a surplus and thus exports. By utilizing the SUMIF function in Microsoft Excel, values were added according to the sign convention. This process was done to all variables to avoid confusion between ‘net movement of Phosphorus per commodity group’ and ‘total imports and exports of particular commodity group.’ Despite the assumption that retailing subsystems do not have storage capabilities, a delta value of 0.10 MT-P was recorded due to the lack of P flow that
characterized the consumption of $F_{28}$: Wood production (0.10 MT-P).

Figure 6 Sankey diagram of phosphorus metabolism in retailing subsystem of Province of Quirino for 2018

3.5 Anthropogenic consumption

Due to time and logistical constraints, the researcher was unable to secure data sets on the consumption of detergents and soap but this shortcoming was supplemented by securing a data regarding the average household wastewater generation in rural and urban households in the Philippines. Assuming that even if the P flows were incomplete, the yielding output of detergent usage will still be reflected on the wastewater generation. Based from these, were human excreta and wastewater generation—$F_{72}$, $F_{73}$, $F_{77}$, and $F_{78}$ were the main outputs of the population, accounting the 20.43% of total outflows. On the other hand, majority (44.65%) of the phosphorus inflows for this subsystem went to rural population despite this metabolic actor having zero-delta value. Overall, the inflow-outflow ratio of this subsystem was 0.331.

Figure 7 Sankey diagram of phosphorus metabolism in anthropogenic consumption subsystem of Province of Quirino for 2018
3.6. Waste and wastewater
Among the analyzed subsystems, waste and wastewater sector had a different trend. It was observed that this subsystem was an overall accumulator \( (\Delta = +109.86) \). This data result was expected due to: i) inclusion of the sanitary landfills in this subsystem (SLF), and ii) according to an FGD conducted with officials from Quirino Provincial Natural Resources and Environmental Office (PNREO), the Province of Quirino have had no wastewater treatment plant (WWTP). 50.51% of the total inflows were produced by \( F_5 \): Solid waste generation, followed by \( F_7 \): Human excreta from rural population (35.77%) and \( F_8 \): Human excreta from urban population (13.55%). In addition, about 98.32% of the estimated outflow of this subsystem was credited to \( F_4 \): Composting from biodegradable wastes (37.21 MT-P).

The inflow-outflow ratio of wastes and wastewater subsystem was 3.903, the highest of them all.

![Sankey diagram of phosphorus metabolism in wastes and wastewater subsystem of Province of Quirino for 2018](image)

\textbf{Figure 8} Sankey diagram of phosphorus metabolism in wastes and wastewater subsystem of Province of Quirino for 2018

4. Conclusion
This model can provide quantitative basis to support policymaking at the local government unit (LGU) level. This paper creates a proposal on methodical approach of analyzing the mass flows and phosphorus mobilization at a provincial level based on thorough and holistic secondary research. Thereupon, the forestry subsystem has a high imbalance of input and output with the estimated input/output ratio of 0.0129. This indicates a massive outflow vis-à-vis inflow. The main priority area for this subsystem was grasslands and other wooded lands. The biggest contributor to the outflows in the agriculture subsystem was \( F_9 \): Erosion and runoff from croplands, consisted of 7775.89 MT-P or 87.5% of total outflows. It was then followed by \( F_{12} \): Wind erosion from croplands. Based on this ecological modelling, the forestry and agriculture subsystem produce high imbalance in terms of input and output that creates apparent impact to the water environment.

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