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Filling two needs with one deed: Potentials to simultaneously improve phosphorus and nitrogen management in Austria as an example for coupled resource management systems

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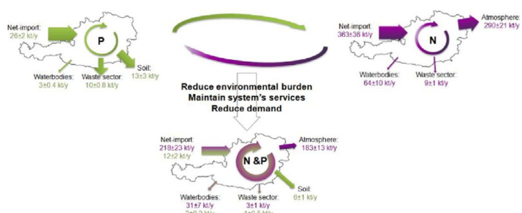
HIGHLIGHTS

- Material flows of several substances can be simultaneously analyzed in a complex system.
- Coupled Material Flow Analyses reveal co-benefits and trade-offs between substances.
- The Austrian phosphorus and nitrogen systems are closely interrelated.
- Highest efficiency gains can be achieved by a combination of different measures.
- Potentials to increase resource efficiency are higher than for emission reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

The tremendous increase in resource consumption over the past century and the environmental challenges it entails has spurred discussions for a shift from a linear to a circular resource use. However, to date most resource studies are restricted to one material or a single sector or process. In this work, a coupled material flow analysis taking the national phosphorus (P) and nitrogen (N) system of Austria as an example for two closely connected resource systems is conducted. Effects of different measures aimed at reducing P and/or N-demand, increasing recycling or reducing emissions to air and water are compared to a reference state (representing the actual situation in 2015). Changes in the mineral fertilizer demand of the system, P and N losses in the waste sector, water emissions of P and N, P soil accumulation and atmospheric N emissions are analyzed. Overall positive feedbacks between measures and between different goals of one measure always outweigh negative ones, which is why the highest efficiency gains (57±4%) can be achieved by a combination of all the 16 measures studied. Potentials for the reduction of mineral fertilizer demand are larger than for emission reduction though, confirming the past priority of environmental protection over resource protection. Although coupling significantly raises model complexity it can be shown that material flows of more than one substance can be simultaneously analyzed in a rather complex system. This may reveal interrelations, co-benefits and trade-offs between different resources that might have been omitted in a mono-substance analysis and thus improve judgment of sustainability and viability of different management strategies.

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1. Introduction

The transition of the world from an agricultural to an industrial society over the past century, which brought about a quadrupling of global population and a 5-fold increase in world GDP/cap, came at the expense of an explosion of global resource use. In 2005 around 60 Gt/yr of materials were extracted and used worldwide, an increase by a factor of eight compared to the beginning of the 20th century. This is linked to a number of problems, such as pressures on and damages to the environment, resource scarcity and distributional conflicts, and therefore poses a serious threat to global sustainability (Krausmann et al., 2009). Moreover, while the world has made progress on mitigating some of the other negative side-effects of industrialization, such as air pollution and acid rain caused by sulfur emissions (Stern, 2005) or the depletion of the Antarctic ozone layer (Hand, 2016), material consumption shows no signs of stabilization or reduction; to the contrary, growth rates during the first decade of the 21st century have been especially pronounced (Schaffartzik et al., 2014).

Among the resources that are of greatest concern in the future is phosphorus (P). Both phosphate rock and phosphorus are among the 27 critical raw materials listed by the EU, substances considered of high importance to the economy and of high risk associated with their supply (Bureau de Recherches Géologiques et Minières et al., 2017). The widespread application of industrial phosphorus fertilizer was crucial to the augmentation of agricultural yields during the green revolution after World War II (Borlaug, 1970) and continues to be an important factor in ensuring global food security. However, phosphate rock is a finite resource. Regardless of ongoing discussion about future availability and a potential peak in P production (e.g. Cordell and White, 2011; Scholz and Wellmer, 2013; Edixhoven et al., 2014), as reserves with pure and easily available P are depleted, extraction becomes more costly and quality of the mined product is declining. Furthermore, P that is currently economically feasible to extract is concentrated in a few countries only, with Morocco accounting for 80% of the known reserves (Jasinski, 2016). Most of the reserves are located in geopolitically unstable regions and some countries restrict extraction for strategic reasons, giving rise to strong price fluctuations on the global P markets (Cordell and White, 2015; Ridder et al., 2012). Despite these challenges, material flow analyses (MFA) such as conducted by Egle et al. (2014), Cooper and Carliell-Marquet (2013) or Senthilkumar et al. (2012) reveal that phosphorus management to date mainly follows a linear approach with high imports for fertilization purposes, the majority of which ends up in landfills, as waste export or is emitted to water bodies, where it can cause eutrophication.

However, scientific, political and industrial interest in recycling phosphorus from waste and wastewater and thus reducing import dependency has been rapidly growing over the past years. Several studies exploring improvement potentials in P management have been conducted (e.g. Hamilton et al., 2017; Klinglmair et al., 2017; Zoboli et al., 2016) and efforts to harmonize national MFAs to facilitate systematic comparison and transfer of lessons learned have been made (e.g. Jedelhauser and Binder, 2015; van Dijk et al., 2016). Policies like the German sewage sludge ordinance (Bundesregierung Deutschland, 2017) or the proposal for the EU Fertilizer Regulation revision (European Commission, 2016) set legal prerequisites to spur recovery and recycling and respective technologies have been developed (Egle et al., 2016). As efforts move from a theoretical to a more and more implementational stage, economic and environmental impacts of different measures and technologies are moving into focus as well (e.g. Egle et al., 2016; Ernst Basler + Partner AG, 2017; Jossa and Remy, 2015; Hanserud et al., 2017). Most of these analyses still view phosphorus management from a single-substance perspective though.

Meanwhile, an even more imminent problem in the near future may be the disruption of the global nitrogen (N) cycle . Unlike P, ammonia (NH_3) fertilizer can be industrially produced from N_2 and H_2 in the Haber-Bosch process. However, this process is very energy-intensive; the production of N fertilizers accounts for 1.1% of global energy use and 0.93% of global greenhouse gas emissions (Dawson and Hilton, 2011; IFA, 2009). Human activities now convert more atmospheric nitrogen into reactive forms than all of the Earth's terrestrial processes combined and four times as much as is estimated to be tolerable for keeping the Earth's system in a stable environmental state (Rockström et al., 2009). Only a fraction of this effectively acts as a plant nutrient though; the remainder is lost to the environment, where it contributes to problems like air pollution (in the form of NO_x), stratospheric ozone depletion (as N_2O), terrestrial and aquatic acidification (NH_x, NO_3), eutrophication of ecosystems (NH_x, NO_3), groundwater pollution (NO_3) and climate change (NO_x, N_2O) (Galloway et al., 2002).

Given the close connection of the phosphorus and nitrogen cycle Rockström et al. (2009) consider them as a single domain in their planetary boundary concept. It therefore seems reasonable to also address inefficiencies in their management in a simultaneous way. However, MFAs of both P and N focus more on the flow patterns of each substance individually than on their interactions, irrespective of whether the analysis is conducted on a sectoral (e.g. Antikainen et al., 2005; Ma et al., 2013; Thaler et al., 2015) or regional (Coppens et al., 2016) basis. Building on existing work by Zoboli et al. (2016) who analyzed the improvement potentials of phosphorus management in Austria based on a detailed national MFA, here, the effects of measures in P management on the N system and vice versa will be studied. This should not only reveal co-benefits and conflicting goals between the two substances, but also, from a methodological viewpoint, foster understanding of whether and how a coupled, multi-substance material flow analysis can generate more robust and meaningful results compared to a mono-substance one. In this respect the coupled MFA of P and N should serve as a case study for coupled resource systems in general.

2. Materials and methods

2.1. Status quo model

Measures to improve Austrian P- and/or N-management were evaluated against the actual situation in 2015 ("status quo model"). To model this reference state, a coupled MFA for P and N, following the methodology described by Brunner and Rechberger (2017) and building on the Austrian MFA for P (Zoboli et al., 2015, 2016), was conducted. The freeware STAN was used (Cencic and Rechberger, 2012) to calculate mass balances for each process in the system, perform error propagation of initial data uncertainties and data reconciliation. The later is based on least squares regression and alters a priori input data so that initial contradictions in the mass balance are eliminated. The a priori uncertainty thereby serves as a weighting factor that determines the extent of adjustment for each data element.

Nine main sectors/processes, relevant for the national P and N management are depicted: Animal husbandry, crop farming, forestry, industry and trade, bioenergy, households and public establishments, wastewater management and waste management. Each of these processes is further described by one or more subsystems, to enable e.g. distinction between food-, timber- and chemical industries or between consumption and soil processes in private households and to show processes such as manure generation and handling in more detail. Exchanges of N and P between these processes in gaseous, liquid and solid form as well as import and exports across country borders are represented by flows of P and N in t/year. In the majority of cases data is present as mass flows of a good (a substances or mixtures of substances with an economic market value Brunner and Rechberger, 2017) reported in national statistic databases or governmental reports and their respective P and N concentrations (mostly