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Supporting phosphorus management in Austria: Potential, priorities and limitations

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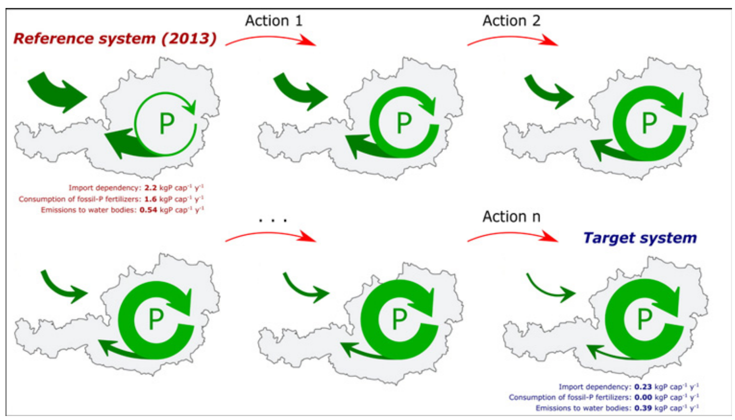
HIGHLIGHTS

- Potentials and limitations for phosphorus stewardship in Austria are quantified.
- Phosphorus import dependency could be reduced from 2.2 to 0.23 kgP cap^{-1} y^{-1}.
- Consumption of fossil-P fertilizers could be completely replaced.
- Emissions to water bodies could be reduced by 28%.
- Systemic approach is essential to set priorities for decision making.

GRAPHICAL ABSTRACT



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ABSTRACT

Protecting water bodies from eutrophication, ensuring long-term food security and shifting to a circular economy represent compelling objectives to phosphorus management strategies. This study determines how and to which extent the management of phosphorus in Austria can be optimized. A detailed national model, obtained for the year 2013 through Material Flow Analysis, represents the reference situation. Applicability and limitations are discussed for a range of actions aimed at reducing consumption, increasing recycling, and lowering emissions. The potential contribution of each field of action is quantified and compared using three indicators: *Import dependency*, *Consumption of fossil-P fertilizers* and *Emissions to water bodies*. Further, the uncertainty of this assessment is characterized and priorities for the upgrade of data collection are identified. Moreover, all the potential gains discussed in the article are applied to the reference situation to generate an ideal target model. The results show that in Austria a large scope for phosphorus stewardship exists. Strategies based exclusively either on recycling or on the decline of P consumption hold a similar potential to reduce import dependency by 50% each. An enhanced P recycling from meat and bone meal, sewage sludge and compost could replace the current use of fossil-P fertilizers by 70%. The target model, i.e. the maximum that could be achieved taking into account trade-offs between different actions, is characterized by an extremely low import dependency of 0.23 kgP cap^{-1} y^{-1} (2.2 kgP cap^{-1} y^{-1} in 2013), by a 28% decline of emissions to water bodies and by null consumption of fossil-P fertilizers. This case study shows the added value of using Material Flow Analysis as a basis to design sound

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management strategies. The systemic approach inherent to it allows performing a proper comparative assessment of different actions, identifying priorities, and visualizing a target model.

1. Introduction

The need for enhancing phosphorus (P) management in most countries is driven by two major goals: protecting surface waters from eutrophication and ensuring future food and energy security under scenarios of uncertain supply (Withers et al., 2015). The latter is particularly true for European countries, as confirmed by the recent inclusion of phosphate rock into the revised list of Critical Raw Materials (EC, 2014). Further, the proper management of P-rich flows can strategically serve as example within the ambitious framework of a circular economy that shall ensure a sustainable and competitive economy by minimizing the generation of waste and by maintaining the value of products, materials and resources for as long as possible (EC, 2015).

The first step essential to achieve these objectives is the profound understanding of the status quo, which allows identifying losses, inefficiencies and processes that require action. This was done in Austria by Egle et al. (2014b), who performed a detailed Material Flow Analysis (MFA) study at the national level for an average year within 2004–2008. Zoboli et al. (2015a) carried forward this work, by shedding light on the dynamics of the system, on the temporal development of management performances and on the uncertainties affecting the results.

Once the current situation has been thoroughly analyzed, it is necessary to move forward and to assess how it can be optimized. A number of studies have investigated in detail specific issues in Austria, namely the potential of P recycling from wastewater and sewage sludge (Egle et al., 2014a), the potential impact of changing dietary habits on nutrients flows (Thaler et al., 2015), and the performance of the national agri-environmental ÖPUL programme in reducing diffuse nutrients emissions (Zessner et al., 2013). Nevertheless, the holistic assessment of the optimization options, that provides decision makers with a comprehensive perspective and with the capability of setting priorities, is still missing.

Withers et al. (2015) have recently reviewed a number of management strategies to address P-related challenges in Europe and they have put forward a framework of 5R stewardship (Re-align P inputs, Reduce P losses, Recycle P in bioresources, Recover P in wastes, and Redefine P in food systems). The main objective of this work is to contextualize such strategies in a specific case study, with the intent to optimize it, by addressing the following questions: to which extent are these strategies applicable in Austria and which limitations exist? Since knowing the relative contribution of different options to the overall P management can be very helpful in setting priorities, the potential effect of each of them is quantified using three indicators of the national performance: *Import dependency*, *Consumption of fossil-P fertilizers*, *Emissions to water bodies*. Further, given the crucial role of data for the accurate assessment of the status quo and for the monitoring of future management, major information gaps are discussed and priorities for improvement are identified. The last objective of this study is the modification of the reference situation, based on the assessment of the optimization potential, to produce a target model.

2. Materials and methods

2.1. Reference year – losses and inefficiencies

This study is based on the Austrian MFA of P, which was developed through the methodology described by Brunner and Rechberger (2004). Detailed information regarding model structure, flows calculation and data sources is provided in Zoboli et al. (2015a). For the present work, the time series of P budgets has been extended to the years 2012 and 2013 in order to analyze a more updated model and the most recent year, 2013, is chosen as reference (Fig. 1).[1]

The detailed system overview provided by the MFA model unveils the weak points where actions can be taken to improve national P management. A major loss of P, equal to approximately 6300 tP y^{-1}, is occurring via sequestration in landfills and cement kilns. Other 2600 tP y^{-1} are exported through P-rich waste flows such as meat and bone meal, instead of following a route for domestic recycling. In addition to this, 2000 tP y^{-1} are contained in material employed as substrate for landscaping activities and are therefore lost as productive resource. The budget also shows an inefficient accumulation on private and public green areas, for a total amount of ca. 2000 tP y^{-1}. Thanks to a major reduction of P mineral fertilizers use in agriculture and to the decline of the total livestock (BMLFUW, 2014b) and consequently of the manure loads, the P surplus accumulation on agricultural soils has largely decreased over the past two decades. Nevertheless, it is still positive, with a surplus equal to 2300 tP y^{-1} (0.78 kgP ha^{-1} y^{-1}). Although surplus is usually defined as total inputs minus agricultural outputs, in this work losses to the environment are also included, so that the estimated optimal balance can also be sustained in the long-term. The average dietary intake of 1.6 gP cap^{-1} d^{-1} is too high and exceeds the nutritional recommendations of the German Nutrition Society (DGE et al., 2003). As concerns emissions to surface water, point discharges have dramatically declined thanks to the enhanced P removal from wastewater, but diffuse emissions are still considerable (3600 tP y^{-1}). Their further decline is imperative, both to meet the target levels of P loads reaching the Black Sea (ICPDR, 2015) and to achieve the good ecological status defined by the Water Framework Directive in the streams that still fail due to the exceedance of orthophosphate values (BMLFUW, 2015,2013,2009).

2.2. Fields of action

The applicability and relevance of the different management strategies put forward by Withers et al. (2015) are contextualized to the Austrian case. The potential improvement with respect to 2013 is estimated and barriers and opportunities are discussed. In total 15 fields of action are considered, each of which addresses the management of a specific flow or process and which can contain one or more measures. They are grouped into three categories: 1. Increase of P recovery and recycling; 2. Reduction of P demand and consumption; 3. Reduction of emissions to water bodies. Further, the uncertainty affecting this assessment is discussed and priorities for the improvement of data quality are pointed out. Some flows are unavoidably affected by more than one field of action. Therefore, they are mentioned in multiple sections, but they are not double accounted for.

2.3. Indicators

The relative contribution of each field of action on the overall national P management is quantified through three indicators: *Import dependency*, *Consumption of fossil-P fertilizers* and *Emissions to water bodies*.

[1] Atmospheric deposition flows (820 tP y^{-1} and 1400 tP y^{-1} for agricultural and forestry soils, respectively) have been removed, because in reality they do not constitute external imports into the system (but rather mobilization of internal stocks) and therefore they may lead to the underestimation of the input necessary to maintain in the long-term a P balance in agricultural soils.

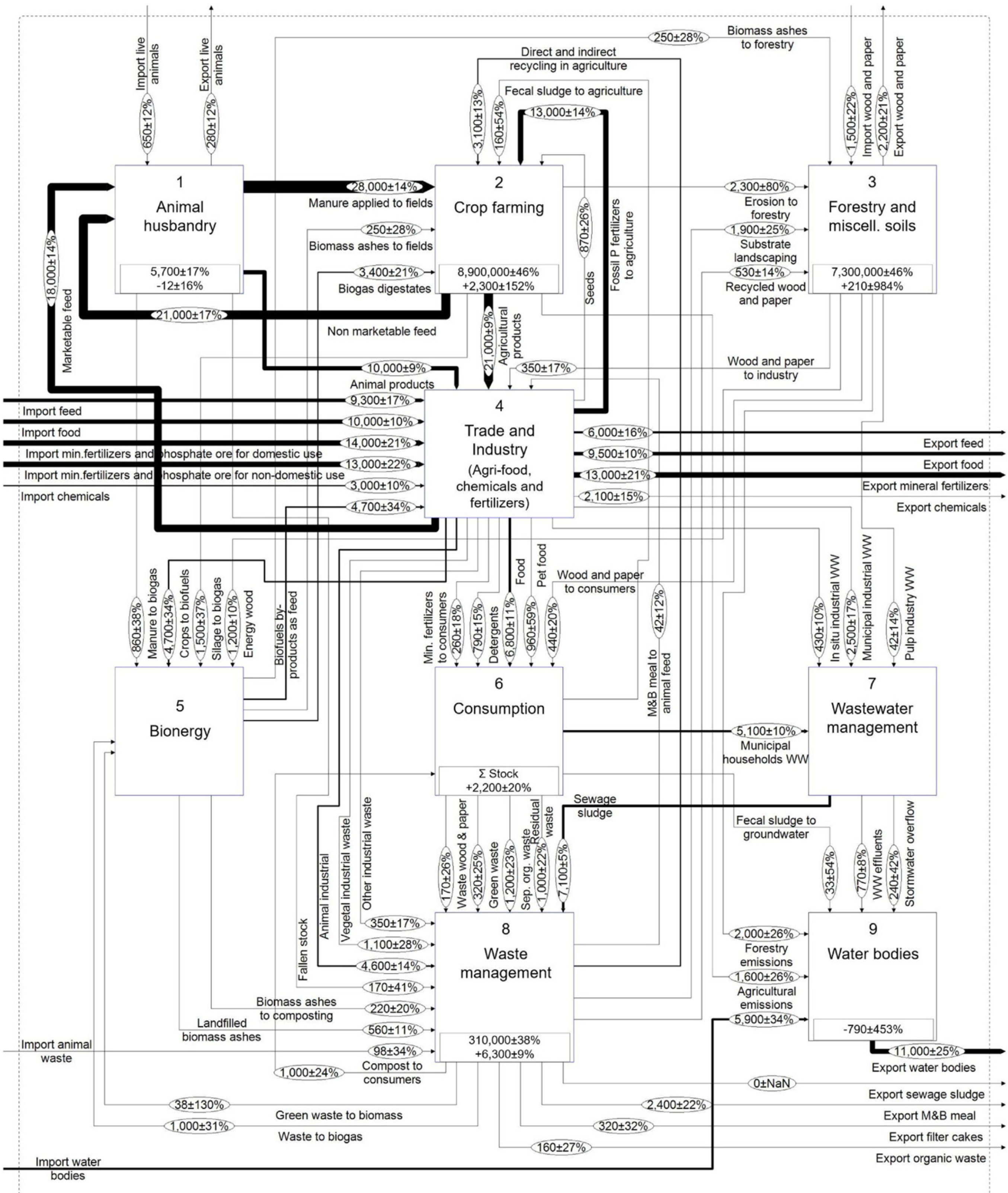

Fig. 1. Austrian phosphorus budget for the reference year 2013 (unit: tP y^{-1}).

Import dependency, as the name suggests, measures how dependent the country is from imported P and was first put forward as indicator of national P management under the name "Net imports" by Cooper and Carliell-Marquet (2013). Reasons for being dependent from imports lie in excessive resource demand, inefficient production chains as well as in losses via sequestration in final sinks and via export of valuable waste materials. It is calculated as net import of P in economic goods. It does not include import/export via surface waters, because it is meant to reflect the economic dependency of the country from imported P. Reducing dependency on imports would make Austria less subject to the price volatility of international commodity markets and to future supply uncertainties.

In *Import dependency*, P embedded in all material flows is considered in an aggregated form. Nonetheless, it is also worth distinguishing between fossil P used to produce mineral fertilizers and other goods. Therefore, the specific contribution to *Consumption of fossil-P fertilizers* is also assessed.

The main reason to evaluate separately the effect on *Emissions to water bodies* is that this indicator addresses the management of P seen as a pollutant, whereas the other two regard P as a critical resource.

2.4. Uncertainty of the assessment

The comparative assessment of the different fields of action via the three indicators is also accompanied by a characterization of its uncertainty. The uncertainty of the MFA flows has been systematically characterized and quantified in (Zoboli et al., 2015a) through a novel approach developed by Laner et al. (2015). In order to account also for the uncertainty affecting the proposed actions and to express the results in a simple and straightforward way, the following procedure has been followed. If the MFA flows related to a given field of action have less than 10% uncertainty and there are no significant gaps of data that hinder a proper estimation of the scope for improvement, the overall uncertainty is defined as *Low*. If MFA flows are affected by more than 50% uncertainty and/or the estimation of the potential is associated with major data gaps or with complex system feedbacks, the overall uncertainty is depicted as *High*. *Moderate* describes intermediate cases.

2.5. Model optimization

Based on the assessed potential of the selected fields of action, the model of the reference situation is modified with the goal of minimizing import dependency, use of fossil-P fertilizers and emissions to water bodies.

The proper design of a national strategy would require a multi-criteria optimization that also considers costs, social acceptance and other environmental impacts in order to account for trade-offs between different objectives and for possible rebound effects. Such a complex approach lies beyond the scope of this article and will be addressed in future research, through the combination of MFA with Life Cycle Assessment and Cost Analysis. The focus here is on one-dimensional optimization, as the first necessary step to understand what could be achieved and which limitations exist.

3. Results

3.1. Increase of P recovery and recycling

3.1.1. Increase of P recycling from meat and bone meal

The handling, use and disposal of animal by-products in the EU is strictly regulated on the basis of three categories that reflect the level of risk for public and animal health (EC, 2011,2009). Category 3 (C3) material is considered low risk and can be employed in biogas, composting, organic fertilizers and feedstuff processing facilities. Category 2 (C2) is considered high risk, but with appropriate pre-treatment can also be used in biogas and composting plants as well as for organic fertilizers production. Category 1 (C1), on the contrary, is high risk and must be incinerated and/or appropriately disposed of. Out of the 86,100 t of meat and bone meal produced in Austria in 2013, half was regarded as low risk C3, whereas the other half belonged to C1 and C2 (BMG, 2013). 27% of the total meat and bone meal found direct application as agricultural fertilizer and 1% was employed for pet food production. Another 19% was incinerated (mainly as substitute fuel in cement manufacturing plants due to its high calorific value), whilst the rest (53%) was exported to be incinerated, employed as fertilizer and for feed production abroad (BMLFUW, 2014a). Export has dramatically increased over the past years, at the expense of domestic incineration and fertilizer use.

The national recycling rate could be improved in different ways. In the first place, there are 20,000 t of C3 meat and bone meal (approximately 1000 tP y^{-1}) that could be applied as organic fertilizers, either directly or indirectly, instead of being exported. A second approach would be the P recycling from the ashes that stem from the incineration of meat and bone meal. This would imply ceasing its usage as secondary fuel in cement kilns, in favor of its mono-incineration or co-incineration with other P–rich materials such as sewage sludge. Since more than 85% of P can potentially be recovered from the ashes, approximately 2000 tP y^{-1} could be recovered every year, provided that the whole amount of C1 and C2 followed this route. Further, if the ashes were directly integrated into the existing industrial production of mineral fertilizers instead of being processed through a specific P recovery technology, the recycling potential would raise up to 2240 tP y^{-1}. Another relevant aspect worth being mentioned is the fact that the C1 and C2 meat and bone meal mostly (about 85%) derives from C2 material (BMLFUW, 2014a). If C1 and C2 are mixed, they all need to be managed as C1. The strict separate handling of the two categories would allow the recovery of approximately 1800 tP y^{-1}, although this would imply in some cases substantial modifications to the current practices and existing facilities.

An important source of uncertainty affecting these results concerns the P concentration in meat and bone meal, which can vary between 3% and 6.6% (Garcia and Rosentrater, 2008). The estimates assume an average and homogeneous P concentration of 5.2% (resulting from the mass balance), but it would be useful to perform a specific survey to assess more exactly the recycling potential of the different categories and the specific flows.

3.1.2. Increase of P recycling from sewage sludge

In 2013 Austria generated 240,000 t (dry matter) of municipal sewage sludge that contained approximately 6600 tP (BMLFUW, 2014a, 2014c). Only 16% was directly applied in agriculture and 10% indirectly after composting; 49% was incinerated, 22% used in landscaping activities and 3% landfilled after biomechanical stabilization (BMLFUW, 2014a). A considerably higher share of direct or indirect (via composting) agricultural application in the future is not realistic, since it is banned or partially restricted in most federal states.

Egle et al. (2014a) performed a comprehensive assessment of the technologies currently developed or under development to recover P from wastewater and sewage sludge. By combining their outcomes with the specific traits of the national wastewater treatment infrastructure, they estimated an actual recovery potential ranging from 0.16 to 0.81 kgP cap^{-1} y^{-1}, i.e. from 1300 to 6700 tP y^{-1}, depending on the type of technology and related investment effort. If the calculations of the report are adjusted to the updated values of total P load in municipal sludge, which slightly decreased over the past years, the maximum recovery potential with respect to the year 2013 corresponds to 0.74 kgP cap^{-1} y^{-1}, i.e. 6200 tP y^{-1}.

Two main sources of uncertainty could be identified. The first one concerns the current use of sludge, which is given in highly aggregated categories. The second stems from the technological performance of P recovery, in terms of product quality, costs, energy and chemicals consumption. In order to reduce these uncertainties, there is a strong need for full-scale demonstration plants. Nevertheless, as summarized in the review by Kabbe et al. (2015), the primary obstacles to P recycling from sewage sludge are no longer technological, but are rather linked to the lack of legal framework and secure market for recycled products. Therefore, the priority for national management should be to ensure a level playing field for all fertilizers.

As for industrial sewage sludge, P recycling may represent an interesting business opportunity for a handful of industries, e.g. in the agri-food or paper sectors, but from a national perspective this P flow is too low to exert a significant effect on the three indicators considered here.

3.1.3. Increase of P recycling from compost

In the year 2013, approximately 3000 tP were contained in compost products (including composted sewage sludge). According to a governmental survey (BMLFUW, 2005), one third of this compost was applied in agriculture, another third was used for private and public gardening, and the rest was employed in landscaping activities. The last one of these applications needs large volumes of material but does not necessarily make use of the nutrients contained in it. Therefore, compost could be replaced with other less valuable materials, by making 1000 tP y^{-1} available for agriculture, provided that it complies with the quality requirements regulated by the Compost Ordinance, (BMLFUW, 2001). Moreover, on the ground of the considerable surplus being accumulated on private and public green areas, it can be argued that also the large use of compost in gardening activities may not be optimal from a national P management perspective and that it shall be rather employed in agriculture.

This field of action is affected by a significant lack of public data. The last published data on compost production refers to 2009 (BMLFUW, 2011a), the last study assessing the share of different uses of compost products dates back to 2005 (BMLFUW, 2005), and the range of P concentration given in these reports is very broad (0.4–1.3 P2O5% of dry matter). Therefore, both to better assess the potential optimization of P recycling through this route and to assess the future performance, a more structured data collection is required.

3.1.4. Increase of P recycling from digestates

In 2013, approximately 3400 tP were returned to agricultural fields via anaerobic digestates. These were generated in 380 biogas plants of primarily small-medium size highly distributed on the whole territory (Energie-Control Austria, 2014). Therefore, their current use as agricultural amendment does not pose problems of geographical concentration and surplus accumulation and does not present further potential for resource use optimization.

Nonetheless, the experiments performed by Stutter (2015) indicate that anaerobic digestates show a potentially high risk of P leaching; it is thus essential that strategies to minimize this risk are implemented, such as limiting application to periods of crop growth.

As reported by the review of Möller and Müller (2012), anaerobic digestates exhibit a wide range of P concentration (0.6–1.7% of dry matter) due to the high variability of the feedstock composition. Therefore, the current lack of national monitoring of material and nutrients flows in this sector gives rise to considerable uncertainties.

3.1.5. Increase of P recycling from biomass ashes

The utilization of ligneous and herbaceous biomass for heat and electricity production has increased substantially in Austria in the past years. In 2013, this industry generated 127,000 t of wood and straw ashes (BMLFUW, 2014a) that given their average composition (Obernberger and Supancic, 2009) contained approximately 1200 tP. They are partially applied in agriculture and forestry. In addition, the Compost Ordinance (BMLFUW, 2001) allows and regulates their use as additive in composting. However, ca. 44% are still being landfilled. A target of 100% recycling is not realistic, on the one hand because the heavy metals content of a fraction of these ashes impedes their direct use in agriculture and composting and on the other hand because their relative low P content hinders the utilization of P recovery technologies. The heavy metals rich fraction consists mainly of fine fly ashes, which represent approximately 2–15% of the total weight (Obernberger and Supancic, 2009). Hence, it can be roughly estimated that 400 tP could be additionally recycled in agriculture or forestry. At the beginning of 2011, new and updated national guidelines were published with the aim of fostering the use of these ashes as fertilizers (BMLFUW, 2011b). This document sets the basis for an enhanced recycling, by promoting the harmonization and the simplification of regional legislation and of local administrative procedures.

The legislation also prescribes the establishment of registers for the application of ashes in agriculture and forestry, which shall considerably improve the currently available information on this usage.

3.1.6. Increase of P recycling from manure

Austria is neither characterized by a segregation of animal husbandry and crop systems nor is its livestock production as intensive as it is in other countries. It can thus be reasonably assumed that manure application is not provoking nutrient inbalances. Nevertheless, best management practices are not yet fully put into practice and still offer scope to reduce fossil-P fertilizers consumption, but a major lack of information hinders its quantification. Further, as shown by Velthof et al. (2015), there is a pressing need for harmonization of methods and data regarding excretion factors of livestock across Europe.

3.1.7. Improvement of municipal and industrial organic waste collection and management

The separate collection and recycling of the organic fraction of municipal solid waste (MSW) has increased substantially over the past 20 years, but approximately 1000 tP are still contained in residual waste and are therefore lost via incineration or disposal in landfills. Austria already meets the Waste Framework Directive (EU, 2008) target of 50% overall recycling of MSW by 2020 and it also complies with the Landfill Directive (EU, 1999), by currently landfilling less than 3% of biodegradable MSW. The national organic recycling rate is 33% and it is characterized by strong regional differences (EEA, 2013). If a 50% target were set on a national level, 300 tP y^{-1} could be additionally recovered.

In 2013, approximately 1,400,000 t of organic by-products and waste were generated by the food processing and retail industry. To a large extent, they were either employed for feedstuff production or recycled via composting and anaerobic digestion. Nevertheless, a relatively small fraction of 160 tP embedded in dairy by-products was exported.

These results are affected by considerable uncertainties, stemming from the P content in MSW based on an relatively outdated study (Skutan and Brunner, 2006) and from the high level of aggregation of the data on the usage of industrial by-products. Hence, the modest potential assessed here might actually be higher.

This field of action does not end at optimizing the management of generated waste, but it should also address its prevention. The Federal Waste Management Plan 2011 includes a Waste Prevention Programme (BMLFUW, 2011a). Out of the 5 areas that are prioritized, two address household and food waste. The first objective of the Programme is to identify the potential for reduction, which due to lack of sufficient information is left out of the present analysis.

3.2. Reduction of P demand and consumption

3.2.1. Achievement of a balanced and healthy diet

Thaler et al. (2015) investigated the potential impact that a shift towards a healthy and balanced diet in Austria would exert on the nutrients fluxes at national scale, compared to the reference period 2001–2006. They estimated that aligning the dietary habits with the recommendations of the German Nutrition Society and the World Health Organization (60% less meat and dairy products, 13% more corn, rice and potatoes and 63% more fruit and vegetables) would imply a 5–6% decline of P diffuse emissions to rivers and a 20% reduction of P net imports, which would largely affect feedstuff and other biomass flows and only to a smaller extent mineral fertilizers. As outlined already by Metson et al. (2012) and by Cordell et al. (2009), it is the very low nutrient use efficiency of animal husbandry that explains the outstanding impact of diet on nutrients flows.

As shown by the scenarios investigated within the study, such estimations are sensitive to the structure of the agricultural system that would accompany such dietary shift (e.g. share of organic farming, share of self-sufficiency versus international trade and intensity of land use for energy crops). Furthermore, the authors have not analyzed the socio-economic implications of their scenarios. This field of action can therefore play a very important and strategic role, but given the complexity of the involved system feedbacks and the general resistance of the population to behavioral shifts, its applicability and effectiveness are not as straightforward as they are for other measures.

3.2.2. Increase of the use efficiency in crop farming

As most other western countries, Austria has followed during decades the strategy of fertilizing in excess, with the consequent accumulation of a large P stock in the soils. As argued e.g. by Withers et al. (2014) and Schoumans et al. (2015), there is sufficient scientific evidence as well as compelling resource, economic, and environmental reasons to shift from an insurance strategy of oversupply to a more efficient and targeted crop fertilization. Schröder et al. (2011), in their review of measures aimed at improving P use efficiency in agriculture, put forward as "low hanging fruits", i.e. measures that could be rapidly implemented and pay for themselves, the adjustment of inputs to outputs and the revision of fertilizer recommendations.

Thanks to the declining trend of mineral fertilizers consumption, in Austria many progresses have been made in balancing inputs and outputs. For the year 2013, a surplus of 2300 tP y^{-1} (0.78 kgP ha^{-1} y^{-1}) was estimated. That year however was extraordinary, in that it was characterized by an extended drought and consequently by low production levels. In 2011 and 2012, a greater agricultural output was achieved, which resulted in less surplus, equal to 1800 and 500 tP y^{-1} (0.61 and 0.17 kgP ha^{-1} y^{-1}), respectively. The achievement of a perfect balance may not be realistic, but the positive surplus values show that there is still room for further reduction of fossil-P fertilizers consumption (1500 tP y^{-1} if the average surplus of the years 2010, 2011 and 2012 is considered). A revision of the fertilizer recommendations might be an effective mean of strengthening and maintaining the declining trend.

However, in order to sustain in the long-term high levels of crops production with reduced fertilizer application rates, more sophisticated approaches might be required, e.g. methods to make use of soil P legacy, maintenance of soil quality, or breeding of crops with lower P requirements (Schröder et al., 2011; Withers et al., 2014). Furthermore, targeted fertilization could contribute to decrease P emissions through surface runoff, which account for ca. 6% of the total P emissions to water bodies (Schilling et al., 2011), and in the long term also to the emissions through other pathways (mainly erosion), since the legacy P in the soil would gradually be reduced.

Unlike other countries, such as France for example (Senthilkumar et al., 2011), Austria does not present strong spatial differences due to geographical segregation of crop and livestock systems; therefore national aggregated soil balances do not mask local opposite unbalances and are appropriate for future assessments.

As far as it concerns data, priorities should be set on the harmonization, validation and update of excretion factors of livestock (see chapter *Increase of P recycling from manure*) and of the P concentration in agricultural products. As shown by a French survey (COMIFER, 2007), the P content in several types of crop and fodder has considerably changed from the 1990s.

3.2.3. Optimization of P content in animal feed

Total P content in feedstuff often exceeds animal requirements in order to overcome limited P digestibility in plant and mixed feed. Alternative ways to achieve a higher efficiency exist however, e.g. feeding in accordance with growth phases, lowering phytate-P content, adding phytase enzymes or using more digestible feedstuff (Schoumans et al., 2014). For the farmers, this could imply savings but also higher costs, depending on the required storage and feeding equipment and on the fluctuating market price of feedstuff ingredients.

Austria has currently no structured nutrients monitoring at farm scale. This renders difficult to properly assess the current state of implementation of such techniques. According to the studies of Kebreab et al. (2012) and Maguire et al. (2005), dietary total P could be reduced up to 20% without affecting livestock performance. Such a high theoretical potential would per se justify an effort in increasing data availability. In addition, dietary P reduction would directly translate into a decline of P content in excretions. On the one hand, this would lead to lower P emissions wherever inappropriate application of manure causes losses to water bodies, although such effect is not quantifiable in this study. On the other hand, in case of efficient use of manure and neutral agricultural balance, the reduction of P in manure would have to be compensated through more fertilization. Given the existence of agricultural surplus, this impact is not visible in 2013. Nevertheless, these issues are highly relevant from a long-term perspective and they provide additional reasons to enhance data collection.

3.2.4. Reduction of P use in detergents

Since the 1990s, Austria has met the target of 100% "phosphate-free" laundry detergents, by means of voluntary commitments (EC, 2004). About 850 tP y^{-1} are still consumed via automatic dishwasher detergents (Wind, 2007), but they will soon decline too, thanks to the EU Regulation No 259/2012 that has recently introduced specific restrictions (as of January 2017).

3.2.5. Reduction of P use in other industrial processes

Withers et al. (2015) mention the use of ortho-phosphates dosing for controlling lead in drinking waters, but this does not apply to the Austrian case, since raw water used for public supply is practically lead free (Jung and Heiss, 2007).

With respect to other industrial uses, Schipper (2014) lists a number of applications of P, namely for car engines, pesticides, rechargeable batteries and flame retardants. Unfortunately, the only available data concerns pesticides, for which Egle et al. (2014b) estimated a very small flow of about 15 tP y^{-1}. Due to the lack of data, it is thus not possible to assess any real potential for optimization nor to monitor future changes.

3.2.6. Reduction of surplus accumulation in private and public green areas

The national MFA has revealed the presence of P accumulation on public and private green areas at a rate of 2000 tP y^{-1}. This is not a negligible stock accumulation, since it corresponds to 15% of the annual consumption of mineral fertilizers in agriculture. The fact that 80% of total inputs consist of home-composting and of compost products suggests that a different strategy of collection and processing of organic and green waste from households, combined with a more selective sale and usage of compost products, would be required to avoid the built up of such surplus.

Nevertheless, this result is affected by large uncertainties that could be considerably reduced through better information on home-composting and on sales of compost products to privates.

3.3. Reduction of emissions to water bodies

3.3.1. Reduction of point discharges

The connection rate to municipal wastewater treatment plants (WWTPs) is 94.5% (BMLFUW, 2014c). A 100% connection rate is unrealistic, given the rural and dispersed character of the remaining settlements. The wastewater of the non-connected 5.5% of inhabitants is handled either via domestic treatment plants or via septic tanks and the resulting sludge is either transported to municipal WWTPs or applied on agricultural fields. Therefore, the connection rate to municipal WWTPs does not offer further room for improvement, neither to reduce emission to water bodies nor to increase P recovery.

The current total P removal rate from municipal wastewater is 90% (BMLFUW, 2014c). The P load still contained in the effluents is approximately 700 t. The 90% removal rate represents the national average,

Table1
Effect of the fields of action on the national P management, expressed as estimated improvement of each indicator [tP y^{-1}] with respect to the reference year 2013; "nq": non-quantifiable; "-": null.

	Field of action	Scope for reduction of *Import dependency*	Scope for reduction of *Consumption of fossil-P fertilizers*	Scope for reduction of *Emissions to water bodies*	Uncertainty level	Main source of uncertainty	Main challenges
Recycling	Increase of P recycling from meat and bone meal	3240	3240	–	Moderate	P concentration	Legal framework and market uncertainties for recovered fertilizers
	Increase of P recycling from sewage sludge	4200	4200	–	Moderate	Performance and product quality for new recovery technologies	Legal framework and market uncertainties for recovered fertilizers
	Increase of P recycling from compost	2000	2000	–	High	Current use shares; P content	Regulation/coordination of sales in large number of composting plants
	Increase of P recycling from digestates	nq	nq	nq	Low	Feedstock amounts and composition	Large number and heterogeneity of biogas plants
	Increase of P recycling from biomass ashes	400	400		Moderate	Current recycling rate Ash quality	Lack of economic incentives that offset logistical costs
	Increase of P recycling from manure	nq	nq	nq	High	Livestock excretion factors Use efficiency of manure as fertilizer	Enhancement of agricultural advice services
	Improvement of municipal and industrial organic waste collection and management	460	460	–	Moderate	P concentration in MSW Current use of ind. by-products Food waste prevention potential	Resistance of households and similar establishments to further increase separate collection Increase of logistical effort and costs for the municipalities
Consumption	Achievement of a balanced and healthy diet	3700	–	250	High	Complexity of system feedbacks	Resistance to behavioral change Opposition of meat producers
	Increase of the use efficiency in crop farming	1500	1500	nq	Moderate	Livestock excretion factors P concentration in crops	Enhancement of agricultural advice services
	Optimization of P content in animal feed	3700	nq	nq	High	Current state of optimization; complexity of system feedbacks	Enhancement of agricultural advice services
	Reduction of P use in detergents	760	–	80	Low	–	–
	Reduction of P use in other industrial processes	nq	–	–	High	Material flows in industrial applications	Substitutability of P
	Reduction of surplus accumulation in private and public green areas	2000	2000	–	High	Home composting Sales of compost to privates	Resistance to behavioral change Coordination of large numbers of people
Emissions	Reduction of point discharges	–	–	440	Low	Loads and performances of in situ industrial WWTPs	Higher Fe levels in sewage sludge would pose a problem for several P recovery technologies
	Reduction of erosion from agricultural soils	2200	2200	580	High	Retention processes; long-term behavior of "legacy" P	Implementation at large scale; Identification of hotspots
	Indicator value in 2013	18,600 tP y^{-1}(2.2 kgP cap^{-1} y^{-1})	13,200 tP y^{-1}(1.6 kgP cap^{-1} y^{-1})	4600 tP y^{-1}(0.54 kgP cap^{-1} y^{-1})			

with specific performances varying within the range 86–96%. Therefore, a further improvement of up to 400 tP y^{-1} is still achievable.

Driven by the requirements of the Urban Wastewater Directive (EU, 1991) concerning the reporting of the disposal of urban wastewater and sludge by the end of 2005, the data quality regarding the performance of municipal WWTPs has considerably increased in terms of its harmonization, frequency and completeness. As far as it concerns industries with in-situ wastewater treatment, however, only large plants from selected sectors must comply with a legal reporting obligation. From a national perspective, the total load of P emitted by industries is very low (ca. 70 tP y^{-1}), but it can exert a considerable local impact on vulnerable surface waters and therefore in specific situations an improvement of these data should be considered.

3.3.2. Reduction of erosion from agricultural soils

The interest on P total national emissions is driven by the ultimate goal of reducing the load reaching the Black Sea. According to the draft River Basin Management Plan 2015 elaborated by the International Commission for the Protection of the Danube River (ICPDR, 2015), the loads of total phosphorus (TP) have considerably decreased, but they still exceed by about 20% the reference target set at the levels of the 1960s. In the considered period 2009–2012, the specific contribution of the Austrian territory per surface unit was among the lowest of the whole Danube basin, which reflects the success of the efforts addressing point discharges.

Erosion, however, still constitutes about 42% of the total Austrian emissions. Through the empirical nutrient emission model MONERIS, Schilling et al. (2011) estimated that, in the period 2001–2006,

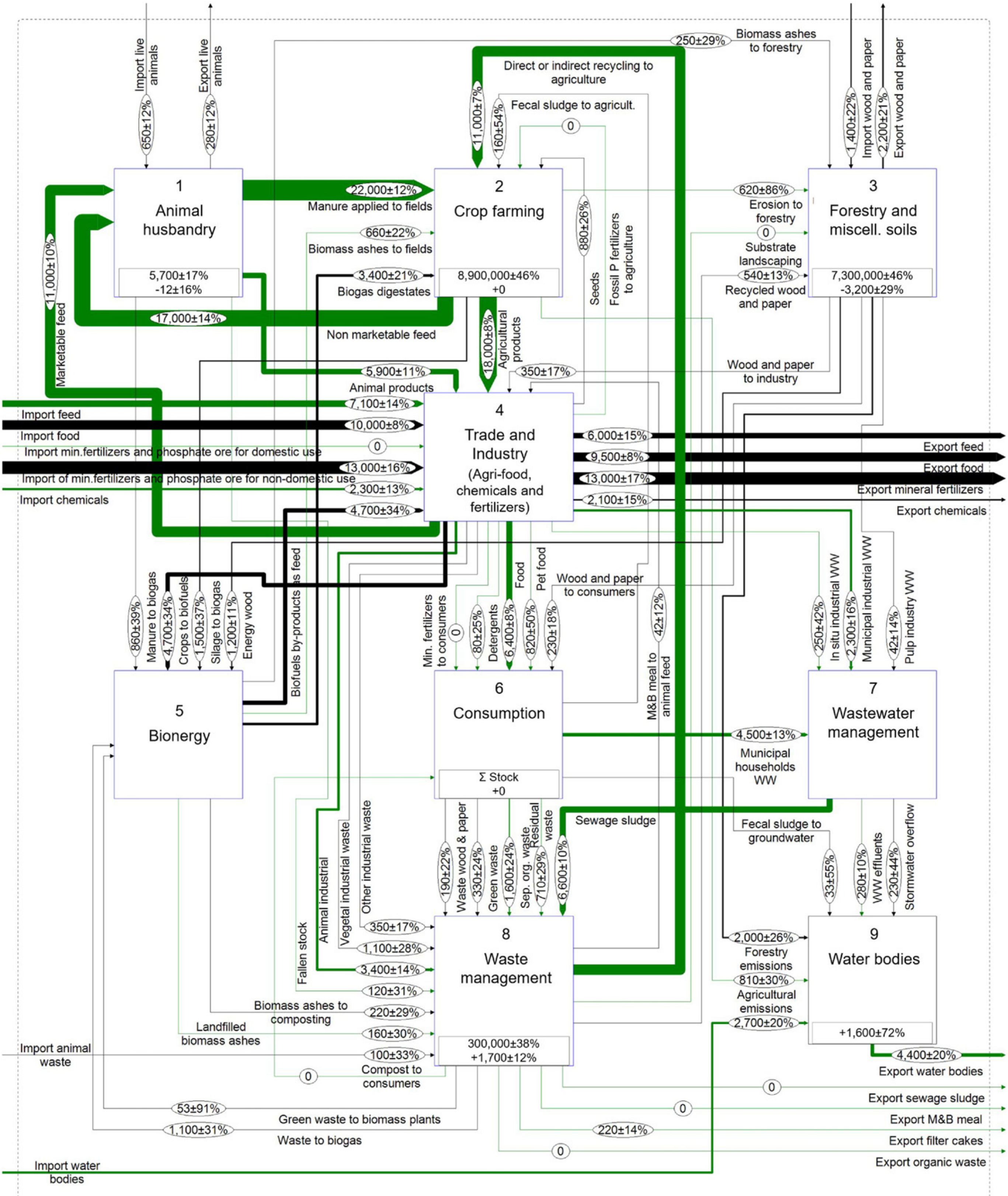

Fig. 2. Target Austrian phosphorus budget based on the reference year 2013 (unit: tP y^{-1}). Objectives for the optimization: reduction of import dependency, consumption of fossil-P fertilizers and emissions to water bodies. Flows that have changed are marked in green.

agricultural soils were responsible for 43% of the TP transported through erosion, whereas natural land accounted for 57% of it. Such high share from natural land is primarily due to the high nutrients export from glaciers (Zessner et al., 2011). Given that the average soil loss in Austria is currently 3.4 t ha^{-1} y^{-1} (Baumgarten et al., 2011) and that a level of 1 t ha^{-1} y^{-1} is generally considered as tolerable and often unavoidable (Eurostat, 2015), it can be estimated that a maximum reduction of soil loss by 70% could be realistically achieved. Such a contraction of soil losses in agriculture would contribute to the decline of total TP emissions by 13% and would also decrease proportionally the need for fertilizers.

Despite the modest potential of this field of action on the national scale, its relevance must not be underestimated. In 2012, 20% of the monitored surface waters could not achieve the good ecological status defined by the EU Water Framework Directive, owing in 75% of the cases to exceedance of orthophosphate limits (BMLFUW, 2013). Moreover, although erosion is responsible for 42% of total P emissions nationwide, it constitutes the dominating pathway in several catchments and especially in those where orthophosphate limits are exceeded.

It is also worth mentioning that this field of action can be extremely cost-effective if its implementation is well designed. As shown by Kovacs et al. (2012) and by Zessner et al. (2013), focusing on phosphorus emission hotspots can remarkably help prioritizing interventions and investments, given that the application of best management practices on less than 10% of the total area would be sufficient to achieve a considerable improvement of water quality.

The quantification of erosion is inherently uncertain, since it has to rely on models for which direct validation is not available (Sharpley et al., 2015).

3.4. Comparative assessment of all fields of action

Table 1 presents the potential gain that can be achieved through each field of action.

The group of measures aimed at enhancing P recycling holds a noteworthy scope to lower *Import dependency* and *Consumption of fossil-P fertilizers*, with meat and bone meal, sewage sludge and compost representing the most relevant flows, whereas other waste materials can contribute only marginally. The combined recycling from all waste flows could replace more than 75% of the present use of fossil P for mineral fertilizer. If compared for instance with the findings of Senthilkumar et al. (2014), who estimated for France a substitution potential of merely 21%, this high value makes evident the extraordinary potential of P recycling in Austria. From a lumped national perspective, these actions do not alter *Emissions to water bodies*, although specific local impacts can be relevant, as it was discussed in previous chapters.

The scope to decrease *Import dependency* through a decline in P consumption is of a similar order of magnitude, with the most relevant actions being the ones that address diet and P content in feedstuff, followed by use efficiency in crop farming and surplus on green areas. In addition, this group of actions can also contribute to the decline of *Emissions to water bodies* by more than 8%. These can be further reduced through actions on point discharges and erosion from agricultural soils by respectively 10% and 13%.

The assessment of the group of measures aimed at reducing P consumption is affected by larger uncertainty. This owes partly to a more severe lack of data and partly to the complex system feedbacks they depend on.

A crucial aspect that generally needs to be considered when prioritizing actions within a national strategy is the time frame. For the measures put forward in this article, it can be reasonably argued that the effects would appear almost immediately after their implementation, except for the decline of diffuse emissions to surface water which are largely dependent on legacy P. As shown by the analysis of the time series of the Austrian P budget (Zoboli et al., 2015a), once clear and effective decisions are made, P flows can change dramatically even from a year to the next. Nevertheless, what may lead to substantial disparities is the time required for the decision process and for the design of the implementation methods.

3.5. Target model

Fig. 2 displays how the national model would look like if all the measures discussed in this article were fully implemented. Flows that have changed are marked in green, but not the ones that have been slightly altered by the reconciliation process, in order to highlight significant changes only.[2]

Consumption of fossil-P fertilizers is null, which manifests the extremely high potential to lower and replace the use of fossil P without affecting agricultural production. Surplus accumulation does not take place in any soil compartment. However, there is still a partially unavoidable loss of P in landfills that will mainly depend on the efficiency of the applied P recovery processes. *Import dependency* measures 2000 tP y^{-1} (0.23 kgP cap^{-1} y^{-1}) and *Emissions to water bodies* 3300 tP y^{-1} (0.39 kgP cap^{-1} y^{-1}), which represent a reduction by 89% and 28% respectively in comparison to the reference year.

As indicated in Table 1, the actual implementation of the measures discussed in this article faces several different obstacles and challenges. Partial goals may however be realistically achieved in the short-mid term. The sewage sludge produced by the municipal WWTP of Vienna is already being mono-incinerated, which eases and lowers considerably the financial burden of introducing P recovery. Following this example, the other large municipal WWTPs (over 100,000 PE) could also implement this route for their sludge management. Further, it is also likely that struvite recovery will be introduced in the WWTPs that meet basic requirements, given the manifold operational benefits that it offers, although the potential is extremely low given the near-absence of enhanced biological P removal. The recycling of meat and bone meal of C3 does not require any investment nor legal changes and it involves only a very small number of processing plants. Further, the material of C1 and C2 could be incinerated in the facilities employed for sewage sludge, allowing the recovery from P-rich ashes. New regulations for the enhancement of biomass ashes recycling and for the reduction of P content in detergents are already in force and their effects can be expected in the short term. As for the reduction of emissions to water bodies, a 95% removal rate of P from wastewater can be achieved without major infrastructural or operational changes and a decline of diffuse emissions through erosion from agricultural soils by 10% can be expected as result of the agri-environmental programme ÖPUL (Zessner et al., 2013). Therefore, with a moderate effort, in the short-mid term *Import dependency* could be reduced from 2.2 to 1.4 kgP cap^{-1} y^{-1}, *Mineral fertilizers consumption* from 1.6 to 0.87 kgP cap^{-1} y^{-1} and *Emissions to water bodies* from 0.54 to 0.47 kgP cap^{-1} y^{-1}.

4. Discussion

The design of an optimized model is a fundamental complement to the comparative assessment shown in Table 1, since from the latter alone misleading conclusions may be drawn. Although the sum of all estimated potentials for the improvement of *Import dependency* exceeds 100%, it does not mean that Austria could turn into a net P exporter, owing to the existence of trade-offs among different fields of action. Achieving a balanced and healthy diet, for instance, would imply a strong contraction of meat production and consequently a decline of the recycling potential from meat and bone meal. This shows the essential role played by the systemic perspective in the design of a national resource management strategy.

The target model depicted in Fig. 2 represents the maximum that can be achieved to reduce import dependency, consumption of fossil-P fertilizers and emissions to water bodies. For a proper model optimization and for the design of a sustainable national management strategy, however, a multi-criteria study, which takes into account factors likely to show relevant trade-offs with P stewardship, such as costs and other environmental impacts, is required. On the one hand, the actions discussed in this manuscript would bring numerous environmental benefits. For

[2] The year 2013 was characterized by a century flood, which caused extremely high P loads and net P mobilization in the Dabube river. For the visualization of an ideal target system, a more typical situation of water bodies is shown, with average import and export P loads corresponding to the period 2003–2012 (extracted from Zoboli et al. (2015b)) and positive P retention.

example, as concluded by Westhoek et al. (2014), cutting meat and dairy products consumption in Europe to meet dietary recommendations would have a major economic impact on livestock farmers and on other actors involved in the related supply-chain, but it would bring major health benefits, 40% reduction of nitrogen emissions, 25–40% decline of greenhouse gas emissions and 23% per capita reduction of cropland employed for food production. On the other hand, as shown by Remy and Jossa (2015), recovery of P from sewage sludge can reduce environmental impacts such as fossil energy demand, global warming potential, eutrophication of freshwaters and human or ecotoxicity, but it might also result in negative effects owing to high demand of energy or chemicals, depending on the technology and the specific context. These two examples highlight the importance of integrating Material Flow Analysis and Life Cycle Assessment in order to optimize such a complex model, as it was done for example by Vadenbo et al. (2014) for the optimization of sewage sludge management in the Swiss region of Zürich.

Not only the assessment of the potential held by different fields of action is affected by uncertainty, but to some extent also the indicators and their explanatory power. One general source of uncertainty for *Import dependency* and *Consumption of fossil-P fertilizers* is the assumption of a perfect substitution between recycled products and traditional mineral fertilizers. Vogel et al. (2015) for example have found that different recycled products from wastewater show a relative plant uptake compared to triple superphosphate ranging from 84% to 114%. These values however, such as others presented in the literature, are results of greenhouse and laboratory experiments. A certain uncertainty regarding the actual substitution potential at large scale thus still exists. Another source of uncertainty stems from the fact that a high legacy soil P level might lead to a substantial overestimation of the actual fertilizer requirements (Hanserud et al., 2015), (Sattari et al., 2012) and therefore the P demand in this study might have been partially overestimated.

5. Conclusions

There are several strategies to achieve P stewardship, but their applicability and actual potential is highly dependent on the specific context. In Austria, recycling from waste streams offers a large optimization potential. Meat and bone meal, sewage sludge and compost could replace 70% of the currently used fossil P-fertilizers, whereas all the other waste flows combined could provide only a limited contribution of 6%. Actions aimed at reducing P consumption can decrease *Import dependency* by approximately 50%, i.e. by the same level that can be achieved through recycling alone. *Emissions to water bodies* can be reduced by 23% through actions on point discharges and on erosion from agricultural soils and by further 8% through changes in consumption patterns. If all measures selected in this study were implemented, the domestic use of fossil-P fertilizers could be fully replaced, *Import dependency* could be reduced from 2.2 to 0.23 kgP cap^{-1} y^{-1} and *Emissions to water bodies* would decline from 0.54 to 0.39 kgP cap^{-1} y^{-1}, with respect to the reference year 2013.

An important outcome of this work is the essential role played by the MFA systemic approach. First of all, it has allowed the accurate identification and quantification of the flows and stocks involved in the different fields of action. Second, it has enabled the quantification of the relative effect of each of them on the national P management performance through the use of different indicators, without which a proper comparative assessment would have not been possible. Further, it has made possible the generation and visualization of a target model, obtained through the integration of all potential gains in the reference model. The resulting concise though exhaustive overview can be very useful to support decision makers in designing national management strategies and setting priorities, as well as to assist domain experts in fitting their work into a broader context.

As next step, this study needs to be complemented with the analysis of the different costs involved in implementing each field of action. Such assessment is subject of ongoing research.

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