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Transition of the Swiss Phosphorus System towards a Circular Economy—Part 2: Socio-Technical Scenarios

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Received: 26 March 2018; Accepted: 11 June 2018; Published: 13 June 2018

Abstract: A transition towards a circular economy of phosphorus (P) in Switzerland is a multi-faceted challenge as P use is subject to a variety of influencing factors comprising policy interventions, consumption trends, or technological innovations on different spatial scales. Therefore, scenarios for P use that take into account both the social and the technical dimension of change are needed for investigating possible pathways of a transition towards more sustainable P futures. Drawing on the multi-level perspective of transition theory, we develop scenarios on the landscape level, i.e., a balanced and healthy human diet, on the regime level, i.e., P recovery from sewage sludge (ash) and meat and bone meal, and on the niche level, i.e., urine separation. Based on the P system of the year 2015, we assess the quantitative implications of the scenarios for the Swiss P system. While scenario 1 mainly affects the agricultural system by reducing the overall P throughput, scenario 2 significantly changes P use in waste management, because P losses to landfills and cement plants decrease and the production of secondary P increases. Scenario 3 shows little quantitative impact on the national P system. From a qualitative transition perspective, however, urine separation entails fundamental socio-technical shifts in the wastewater system, whereas P recovery from sewage sludge (ash) represents an incremental system adaptation. The combination of flow- and transition-oriented research provides more general insights into how a circular economy of P can be reached. Furthermore, the analysis of P recycling scenarios reveals that transition processes in Switzerland are embedded in a global resource economy. Thus, a sole focus on concepts of national P self-sufficiency and the reduction of Switzerland's P import dependency tend to fall short when analysing the economisation of secondary P materials in the face of transnational resource flows and markets.

Keywords: phosphorus; Switzerland; scenario analysis; substance flow analysis; socio-technical transition; circular economy; human diets; recycling; sewage sludge; urine separation

1. Introduction

Sustainable phosphorus (P) management is a multi-faceted challenge that is affected by a variety of factors including policy interventions and consumption trends, e.g., in fertilizer use, and technological innovations [1]. Hence, in order to analyse future pathways of P systems, it is crucial to consider the transition towards a circular economy (CE) of P as a socio-technical project and apply an integrative perspective that takes into account both socio-economic and material aspects of P management [2]. Although technical innovations, such as P recovery technologies, have gained a prominent role in current debates on sustainable P management, their successful implementation not only depends on technical feasibility but also on various institutional factors such as acceptance, education, politics, legislation, and economic issues [3–7].

One academic concept that has gained remarkable prominence in dealing with the co-evolution of technology and society in change processes is the multi-level perspective (MLP) [8–10]—one of the main pillars of transition theory [11–14]. The MLP considers socio-technical transitions as the result of processes on three different levels: landscape, regime, and niche. The landscape is the external transition context on the macro level. It comprises, inter alia, socio-economic trends, influential external events, norms, values, or narratives that facilitate, hamper or even trigger change processes in the system [8]. Regimes are the institutionalized "rule-set or grammar" [15] (p. 340) on the meso-level. They represent the socio-technical status quo that fulfils societal functions, guides actions within the system, incrementally innovates and adapts to changing external conditions, and in doing so, stabilizes the incumbent system structure. Niches are protected spaces on the micro-level, where radical innovations are created, which eventually might challenge, destabilize, and change or replace regimes.

The value of transition theory in general and MLP in particular is that they shed light on the capacity of socio-technical innovations to reconfigure the fundamental structures of socio-technical systems [16]. Whereas some innovations incrementally adapt incumbent regimes, others induce radical transformations of the overall system structure [17]. This is particularly helpful for analysing the impact of the CE. CE concepts and projects have been criticized for their industry- and growth-oriented approach that manifests and locks in existing structures and economic practices while closing down alternative and more radical discourses, visions, and innovations in resource economies [4,18]. For instance, creating resource cycles would not necessarily provide incentives to reduce the overall resource throughput in the first place marginalizing sufficiency or de-growth approaches [19,20]. Thus, a transition perspective on CE is needed in order to critically assess the capacities of different socio-technical processes in CE projects, e.g., P recycling, to fundamentally change the underlying systems and economic structures.

From this perspective, for the case of circular P management, the question arises as to how different socio-technical developments will affect both P flows and the underlying systems, particularly the agri-food and waste system, in the future. For this, scenarios that take into account the socio-technical dimensions of a CE of P are needed. A number of studies have analysed how P flows change in different social, political, technological, and ecological scenarios. They were conducted with different thematic foci, e.g., scenarios for mineral P depletion [21,22] or for the agri-food system [23,24], and on different geographical scales comprising urban [25–27], national [28–31], regional [32], and global P systems [24,33]. While these analyses provided insights into the theoretical quantitative implications of different scenarios for P use, less attention has been paid to how the scenarios affect the underlying system structures and contribute to socio-technical transformative change. Furthermore, the scenarios developed were mostly based on extreme assumptions, e.g., 100% recycling rates or a complete shift to a vegetarian human diet, on individual assumptions made by the researchers, or on general socio-economic trends, e.g., population and GDP growth. This was due to a lack of data, e.g., on the performance of new recycling technologies, and of concrete policy frameworks and goals hampering the development of more specific scenarios. However, recent efforts in various European countries provide information for better refined scenario assumptions that take into account the specific contexts of the P system under investigation. We use P management in Switzerland as the case for our scenario analysis. In Switzerland, on the one hand, political-legislative interventions in waste management, campaigns for shifts in human diet and technological innovations in P recycling are examples of recent socio-technical developments on a national level. In this context, sustainable P management is linked to debates on how national import dependencies of P fertilizers might be overcome if a geopolitical shortage would emerge. On the other hand, the country's P system is interwoven with a global resource economy, which is why concepts of national import dependency and P self-sufficiency need to be embedded in the broader transnational CE context. Thus, a scenario analysis is needed that accounts for processes on these different scales and assesses their impact on both P flows and the underlying system structures.

The aims of the paper are to:

(i) develop context-specific landscape-, regime-, and niche-related scenarios that (might) affect the Swiss P system in the future;
(ii) assess the quantitative implications of these scenarios for P flows and stocks in Switzerland; and
(iii) compare the scenarios and embed them in the overall socio-technical transition towards a CE of P.

2. Materials and Methods

Our research design comprised three steps: (i) scenario development; (ii) quantitative flow analysis; and (iii) socio-technical transition analysis. For the development of the scenarios, we used the MLP as a framework meaning that we elaborated future scenarios for the landscape, regime, and niche level. For this, we took up current debates, policy initiatives, technological innovations, and research projects, which either directly aimed at achieving a more sustainable P use (e.g., P recycling) or indirectly affected P flows and stocks by altering the use of P-containing mass flows (e.g., food consumption). The specific scenario assumptions were developed based on desk research, i.e., the analysis of current policy initiatives, research projects, and academic papers, and on interviews with experts from the P system comprising actors from government, technology development, waste management, research, and fertilizer industry. Table 1 shows a first overview of the three scenarios. For better readability, we present the detailed description of the scenarios together with the quantitative analysis in the results section.

Table 1. Overview of scenarios developed; VVEA = Swiss Ordinance on Avoidance and Disposal of Waste.

Scenario	Level	Context	Assumptions
Balanced and healthy human diet	Landscape	Government initiative: Swiss Nutrition Strategy 2017–2024 [34]	Food recommendations according to [34]
Implementation of VVEA	Regime	Legislative intervention: VVEA [35]	Full implementation of VVEA, i.e., P recovery from wastewater, sewage sludge or sewage sludge ashes and utilization of P in meat and bone meal
Urine separation	Niche	Research & pilot projects [36,37]	Separate collection and recycling of 20% of total urine on the household & businesses level

The assessment of the quantitative implications of the scenarios for the Swiss P system draws on the methodological approach from part 1 [1], i.e., substance flow analysis (SFA). See part 1 for a detailed description of our SFA procedure. Combining SFA with scenario analysis provides an approach to assess the flow- and stock-related quantitative implications of different scenarios in a CE [38,39]. The current state of the Swiss P system calculated in part 1, i.e., the reference year 2015, served as the basis for our scenario analysis. We used material and P data from this year and adapted and re-calculated flows and stocks in accordance with the assumptions of the scenarios. We calculated the P flows and stocks applying the P monitoring tool [40] and STAN software [41] and visualized them using e!Sankey [42] (see also part 1). We adopted the P system structure of part 1, i.e., its processes (subsystems), flows, and stocks, and slightly adapted it for scenario 2 and 3, where new processes and P flows were needed. This means that, as in part 1, the system boundary of our P-flow analysis is the national Swiss border. However, we are aware that future P management in Switzerland does not take place in an isolated national system but is embedded in and influenced by processes on a global level such as international trade and resource flows, economic and social trends, or global governance. We take up this multi-scalarity in the individual scenarios.

Furthermore, we used the three indicators developed in part 1 in order to systematically analyse and compare the impact of the scenarios on the P system: The total import dependency (TID) relates

P net imports (of the P-demanding subsystems *animal husbandry*, *cultivation* and *chemical industry*) to total P inputs (to these subsystems). The P efficiency plant production (PEP) refers to the subsystem *cultivation* and is the amount of P in domestic fodder and plant-based food production in relation to P fertilizer inputs to soils (manure, mineral fertilizer, organic recycling fertilizer, and sewage sludge). P losses waste management (PLW) refers to the subsystem *waste management* and relates P losses in *waste management* (i.e., P losses in cement plants and landfills, exported P, and P effluent from wastewater treatment plants (WWTP)) to total P inputs (to this subsystem). See also Supplementary Data for more detailed indicator descriptions.

For the transition analysis, we linked the results of our SFA-based scenario analysis to the socio-technical dimensions of human diets, P recovery from the waste system, and urine separation to contextualise the scenarios within the overall transition to a CE of P. For this, we conducted desk research combining our data with theoretical insights from MLP research and empirical findings of related transition studies.

3. Results

In this section, we present the results of the development and analysis of the three scenarios. The system boundary of all scenarios is the Swiss border. While in scenario 1 and 3 we analysed flows and stocks for the overall national system (i.e., the total P system comprising all six subsystems), in scenario 2, we conducted the SFA for the subsystem *waste management* (see Section 3.2.2). The scenarios take up recent political initiatives (scenario 1), legislative interventions (scenario 2), and current research endeavours (scenario 3). The scenarios were developed and analysed separately, that is, no joint scenario analysis combining all three scenarios was conducted. This is because the aim of our analyses was not to investigate one comprehensive Swiss P future and its probability and implications, this would have required the inclusion of many more social, economic, political, environmental, and technological factors. Instead, we aimed at spotlighting different current developments and assessing their quantitative and, in Section 4, qualitative impact on the Swiss P flows and the underlying socio-technical systems.

The following subchapters are structured as follows: First, we give an introduction to the background of each scenario. Second, we describe the scenario including the assumptions made for the calculation. Third, we present the implications of the scenario for the Swiss P flows and stocks.

3.1. Scenario 1: Balanced and Healthy Human Diet

3.1.1. Scenario Background

The role of the human diet in the context of sustainability has been studied from social and environmental perspectives. In developed countries and emerging countries with rising incomes and urbanization trend, the current dietary patterns based on processed foods, meats, oils, refined sugars, and refined fats is causing severe health problems in terms of overweight, obesity, and diet-related diseases, e.g., coronary heart disease or type II diabetes [43]. These diets, in combination with population growth, are intertwined with changes in global agriculture impacting the environmental system. The increasing global demand for animal-sourced food leads to a growing animal husbandry sector resulting in negative externalities such as greenhouse gas emissions, conflicts on land and water use, and high accumulation of manure-based nutrients in soils and surface water causing, inter alia, eutrophication. Thus, scholars have emphasized the need for shifts in human diets in order to improve both human and environmental health [44,45]. This claim has been taken up by governments, which seek to reduce the external costs of unsustainable diets [46–48]. In Switzerland, the government promotes a balanced diet and healthy lifestyle in its Swiss Nutrition Strategy 2017–2024 [34] aiming at setting better framework conditions for healthy diets, increasing knowledge and awareness among citizens, and cooperating with actors along the value chain of the agri-food system in order to make them provide healthier food and meals.

Although these initiatives are not driven by sustainable P use issues, shifts in dietary patterns in Switzerland would inevitably affect the country's P flows and stocks. Various authors illustrated the strong interrelations of human diets and P flows [21,49–51] and dietary shifts were included in a number of P scenario analyses [24,25,27,33,52]. While these analyses mainly calculated the P-related impact of extreme scenarios such as a complete shift to a vegetarian diet, scenarios with more sophisticated assumptions, e.g., balanced diets, have been receiving less attention [30,31].

3.1.2. Scenario Description

Our scenario builds upon the Swiss Nutrition Strategy 2017–2024 [34], which provides recommendations for a change in the consumption of ten different types of foods. It suggests a reduced consumption of meat and fish, eggs, vegetable oils/fats, animal fats, and sugar; and an increase in the consumption of grain/rice/potatoes, vegetables, fruits, dairy products, and nuts/seeds (Table 2). Our scenario builds upon these recommendations and investigates how the implementation of a balanced diet would affect the Swiss P system. For this, we adapted the flows animal-based food and plant-based food according to the recommendations and calculated the feedbacks of these changes on the overall P system.

Table 2. Recommended food consumption compared to consumption in 2014/15 according to FSVO [34].

Food	%
Meat and fish	−68.5
Eggs	−19.5
Milk and dairy products	+50.0
Grain/rice/potatoes	+25.0
Vegetables	+76.5
Fruits	+5.3
Vegetable oils/fats	−34.0
Animal fats	−74.4
Nuts/seeds	+100.0
Sugar	−75.0

A change in diets and, as a consequence, in food demand is likely to affect both national food production and food imports and exports. However, in our analysis, we focused on the effects for the national agricultural system, i.e., *cultivation* and *animal husbandry*, whereas P imports in plant-based and animal-based food remained unchanged in our scenario assumptions. We had to make this simplification in order to calculate the flow-related implications (for additional information on the assumptions made for the three scenarios, see Supplementary Data: Table S1).

3.1.3. Implications for Swiss P System

A shift to a balanced and healthy diet has three major implications for the Swiss P system (Figure 1): (i) Despite an increase in P consumption via food in *households & business* by 4% (+400 t P), total P turnover in agriculture decreases by 22% (−7100 t P) in the subsystem *animal husbandry* and by 10% (−3200 t P) in the subsystem *cultivation*; (ii) the decrease in fodder net imports overcompensates for the increase in mineral fertilizer net imports resulting in a reduction of P net imports to agriculture (−2200 t P); and (iii) P losses via animal by-products decrease by 56% (−2000 t P) (for better readability we round the flow values; see Figures 1–3 for more detailed data).

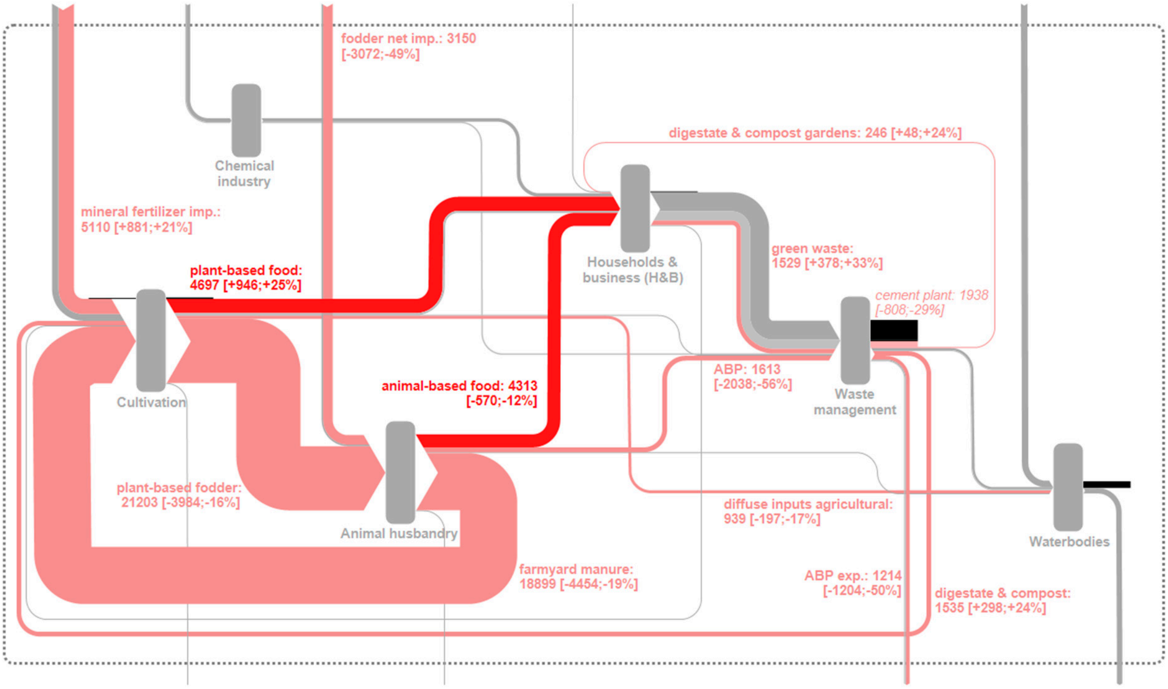

Figure 1. Annual P flows and stocks (in *italics*) [in t P] of Swiss P system in scenario 1 compared to reference year 2015 [dark red: directly affected P flows; light red: indirectly affected P flows]; for detailed information on grey P flows and stocks see part 1 of the paper [1]; ABP = animal by-products.

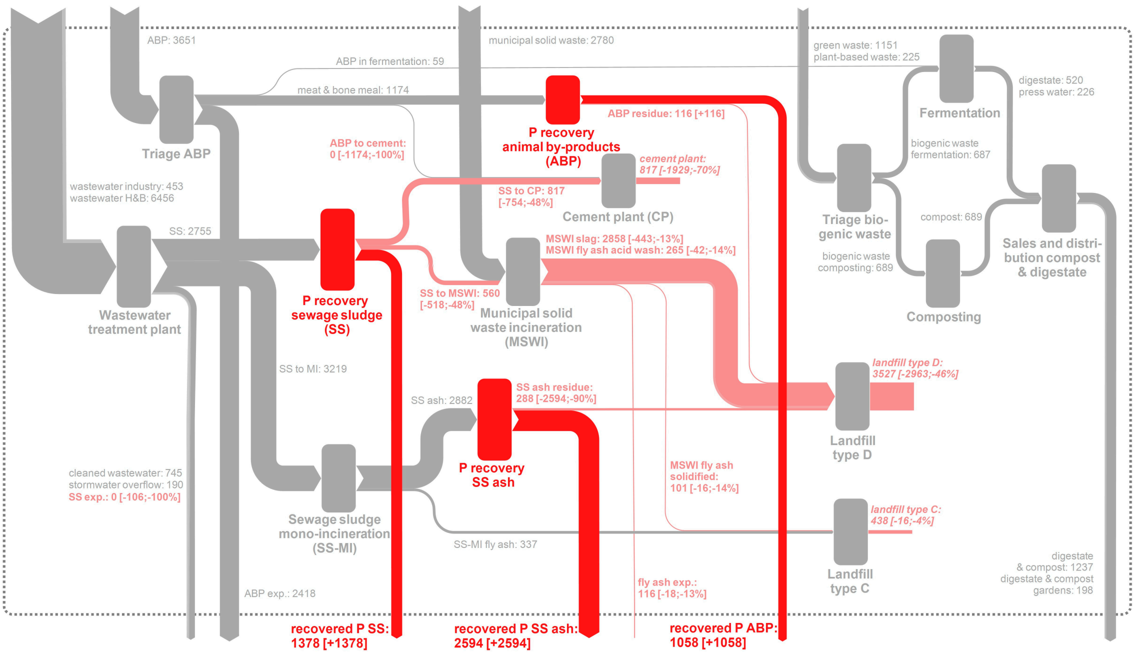

Figure 2. Annual P flows and stocks [in t P] of Swiss P subsystem *waste management* in scenario 2 compared to reference year 2015 [dark red: directly affected P flows; light red: indirectly affected P flows]; ABP = animal by-products; SS = sewage sludge; landfill type C = landfills for stabilised residues with high concentrations of heavy metals and small organic fractions; landfill type D = landfills for slags from incineration processes.

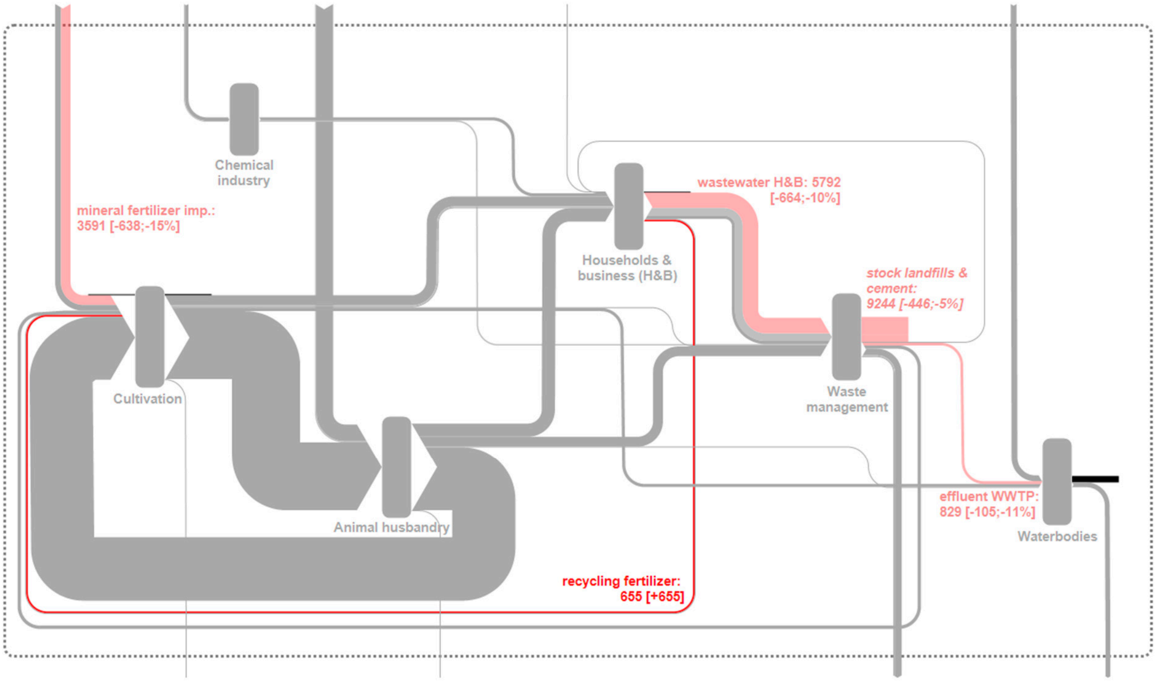

Figure 3. Annual P flows and stocks (in *italics*) [in t P] of Swiss P system in scenario 3 compared to reference year 2015 [dark red: directly affected P flows; light red: indirectly affected flows]; for detailed information on grey P flows and stocks see part 1 of the paper [1].

In the subsystem *household & businesses*, the flows animal-based food and plant-based food are directly affected by the scenario. P in plant-based food increases by 25% (+900 t P) and P in animal-based food decreases by 12% (−600 t P) resulting in the above-mentioned total increase of P inputs to the subsystem. The increase in plant-based food is due to more consumption of grain/rice/potatoes, vegetables, and nuts/seeds, whereas the reduction of animal-based food is because of less consumption of meat/fish and eggs. This reduction, however, is partially compensated by an increase in the consumption of dairy products.

In the upstream part of the Swiss P system, the decrease of animal-based food production and the increase of plant-based food production have several consequences for the in- and outputs as well as the internal flows of the domestic agricultural system. In *animal husbandry*, P outputs in animal-based food (see above), in manure (−19%; −4500 t P), and in animal by-products (−56%; −2000 t P) decrease. These changes mainly stem from the reduced meat consumption and the decrease in the number of animals from around 14 million to 6 million. However, due to the increase in dairy products, the number of dairy cows increases from 700,000 to 900,000 resulting in a change in the domestic manure supply structure. While P in cow manure accounted for 54% of P in total manure in the reference year 2015, it increases to 82% in the scenario. With regard to P inputs to *animal husbandry*, P in feed net imports are reduced by 49% (−3100 t P) and P inputs in plant-based fodder decrease according to the reduction of manure. In *cultivation*, on the one hand, the growing demand for plant-based food leads to an increase in domestic plant-based food production (see above). On the other hand, the reduced production of animal-based food and manure in *animal husbandry* results in a reduction of the cultivation of plant-based fodder by 16% (−4000 t P). The decreased P inputs to soils via manure need to be compensated by more P inputs via mineral fertilizers net imports (+21%; +900 t P). Regarding soil-related P use efficiency, the PEP indicator remains constant at 94%, since the quantities of P in- and outputs change but not the efficiencies in terms of soil management and agricultural practices. As explained in Section 3.1.2, we simplified the calculations by focusing on the implications of the change in diets for the Swiss agricultural system meaning that the changed demand for food was covered by restructuring national food production, which then had indirect implications for fertilizer and fodder imports. Under different scenario assumptions, the changed demand could also be covered by global agriculture, i.e., by importing the required food products, leading to an increase in plant-based food and a decrease in animal-based food.

In the downstream part, the shift to a balanced and healthy diet leads to a decrease of total P inputs to *waste management* by 11% (−1600 t P) resulting in reduced P losses via storage in cement and via outputs from the subsystem. On the input side, the amount of green waste increases by 33% (+400 t P) due to more consumption of plant-based food in *households & business* leading to an increase of P recycling of digestate & compost by 24% (to agriculture: +300 t P; to private gardens: +50 t P) on the output side. The increase of P inputs via green waste is compensated by the above-mentioned decrease of P inputs via animal by-products due to reduced slaughtering in *animal husbandry* resulting in a decrease of P losses via exports (−50%; −1200 t P) and reduced P losses in cement plants (−29%; −800 t P). The PLW indicator slightly decreases from 90 to 86%.

Even though the overall P net imports via mineral fertilizer and fodder decrease by 2200 t P, the TID indicator remains at the level of the reference year (23%). This is due to the fact that the absolute P inputs to agriculture including imports and domestic flows, in particular manure and plant-based fodder, are smaller in the scenario and therefore the relative importance of inputs via P imports remains constant.

3.2. Scenario 2: Implementation of VVEA

3.2.1. Scenario Background

Technological approaches to P recovery from secondary materials such as sewage sludge and meat and bone meal have been receiving growing attention in recent years [53–55]. Since in Switzerland the ban of direct application of sewage sludge on agricultural land in 2006 led to an increase in P losses via mono- or co-incineration of sewage sludge, the Swiss government amended the Swiss Ordinance on Avoidance and Disposal of Waste (VVEA) to re-create the P cycles between the waste sector and the agri-food system [1]. The VVEA requires the technical recovery and recycling of P from municipal wastewater, sewage sludge, or sewage sludge ash and the re-utilization of P in meat and bone meal as of 2026 [35]. Hence, Switzerland is the first country worldwide where the recycling of P from the wastewater sector and animal by-products will be mandatory.

Since the VVEA does not require specific recovery technologies and recycling pathways, it leaves room for different technological approaches. To date, more than 50 technologies have been or are still being developed in various countries recovering P from the aqueous (i.e., wastewater) or the solid phase (i.e., sewage sludge and sewage sludge ash from mono-incineration) of the wastewater treatment process as well as from meat and bone meal [53,56,57]. They are currently at different stages of implementation ranging from bench-scale to fully operating recovery plants at large scale. With regard to P recovery from wastewater and sewage sludge, technologies that produce struvite (e.g., *AirPrex*), dicalcium phosphate (e.g., *ExtraPhos*), or a P-rich slag (e.g., *MEPHREC*) as an output material are currently the most advanced approaches. These materials could then either be directly processed to market-ready fertilizer, as this is already the case for some struvite plants in Germany or the UK, or be re-integrated in P industries. Regarding ash-based recovery approaches, technologies that produce secondary phosphoric acid (e.g., *TetraPhos* or *EcoPhos*) have been implemented in a number of full-scale and pilot plants in various European countries [54]. Being a homogeneous industrial input material, secondary phosphoric acid could be re-integrated in existing industrial P markets, e.g., in fertilizer and feed production but also in non-food related industries. P recovery from meat and bone meal is still at a very early stage, but several recovery technologies for sewage sludge (ash) are expected to also work with meat and bone meal (ash) [57]. Besides the technical process, infrastructural requirements, and the material outcome, the recovery technologies differ with regard to their P recovery rate, financial costs, carbon footprint, practicability, residual materials, and plant availability of the recovered material [53,56,58–60]. For our SFA-based calculation of P scenarios, the P recovery rate is an important issue. While ash-based technologies are expected to recover around 90% of P in the ashes, wastewater- and sewage-sludge-based approaches range between 10% and 90% P recovery depending on the technology [57].

In Switzerland, no recovery plant has been installed yet, but first efforts to implement the VVEA can be identified. The operators of the country's biggest mono-incineration plant in Zurich are planning to implement an ash-based technology for P recovery (*phos4life*) in the form of secondary phosphoric acid [61]. Pilot phase has started in late 2017. There are several further P recovery projects being planned, where pilot phases are already running or likely to be started in early 2018: WWTP Bern (*ExtraPhos*, P recycling from dewatered sewage sludge, producing dicalcium phosphate), AVA Altenrhein (*Pyrophos*, pyrolysis of sewage sludge, producing a P-potash-fertilizer), erzo Oftringen (*EuPhoRe*, chemo-thermal treatment of sewage sludge in a rotary kiln) and ZAB Bazenheid (fertilizer production from meat and bone meal) [62].

3.2.2. Scenario Description

In our scenario, the VVEA is fully implemented, meaning that P is recovered from wastewater, sewage sludge, or sewage sludge ashes and P in meat and bone meal is re-utilized. For ash-based P recovery, we take the capacity and utilization of existing sewage sludge mono-incineration plants in the reference year 2015 as a basis, as there are no plans for building new plants in Switzerland at the moment. P that remains in the ash after recovery is landfilled. P on WWTPs without subsequent mono-incineration is recovered from the aqueous or solid phase. The sewage sludge, containing the residual P, is then incinerated in cement plants or municipal solid waste incineration plants with P ending up in cement or landfills. Regarding P in meat and bone meal, we assume that the VVEA affects P in category 1 (very high risk) and 2 (high risk) materials, which has to be recovered and re-utilized in the future. Since current legislation already allows the utilization of category 3 material (low risk), we adopt the value from our reference study. P recovered from category 1 and 2 materials is then assumed to be recycled in agriculture or P industries. We expect ash-based technologies to play a dominant role for P recovery from incinerated meat and bone meal. Drawing on current data on P recovery rates [57], we assume that 90% of P in mono-incinerated ashes, 50% of P in wastewater and sewage sludge, and 90% of P in meat and bone meal is recovered.

The scenario is calculated for the subsystem *waste management* and not for the overall Swiss P system. This is due to high uncertainties related to the potential demand and markets for secondary P after the recovery process. Even though the specific P recovery approaches and output materials chosen by the decision-makers in Switzerland have become more evident lately (e.g., phosphoric acid in Zurich or dicalcium phosphate in Bern), it is still unclear whether these secondary resources are going to be recycled in Switzerland or exported. This concerns both the geographical place and the economic sector. Within the agri-food system, e.g., in the fertilizer industry, Switzerland has only small capacities for processing secondary P [63]. As a consequence, significant amounts of recovered P might be either exported to countries with bigger industrial P capacities or marketed to non-food-related chemical industries, where, however, the amount of recovered P from the waste sector is also likely to exceed the size of the domestic market. Furthermore, global price trends for phosphate rock and primary P products highly affect whether and where P recyclates are recycled in the future (see Section 4 for a more detailed discussion of these issues in the context of the CE). Due to these uncertainties, we classify secondary P as outputs from *waste management* without further defining their destination.

3.2.3. Implications for Swiss P System

The main implications of the implementation of the VVEA are an increase in secondary P outputs from *waste management* by 98% (+4900 t P) and a decrease in P accumulation within the subsystem by 51% (−4900 t P) (Figure 2). In total, the implementation of the VVEA leads to the creation of 5000 t of secondary P accounting for 48% of P entering the subsystem via wastewater and animal by-products.

P losses in landfills and cement plants are reduced by 51% from 9700 t in the reference year to 4800 t in the scenario. The reduction of P losses finds expression in the PLW indicator, which significantly decreases from 90% in the reference year to 56% in the scenario. A large proportion (70%) of landfilled P stems from municipal solid waste (2800 t P) and is therefore not impacted by the VVEA.

In the wastewater part of the subsystem, 1400 t P from sewage sludge and 2600 t P from mono-incinerated sewage sludge ashes are recovered accounting for 57% of P inputs to WWTPs and 66% of P in sewage sludge. As a consequence, P flows to both cement plants and municipal solid waste incineration plants via sewage sludge decrease by 48% (−800 t P and −500 t P respectively) and to landfill type D (i.e., landfills for slags from incineration) via ash residues by 90% (−2600 t P). With regard to animal by-products, 1100 t P are recovered from meat and bone meal and 100 t P are landfilled. No animal by-products are incinerated in cement plants in the scenario any more (−1200 t P).

The extent to which the scenario affects Switzerland's P import dependency, i.e., TID, depends on the future destination of the recovered P. If the recovered P (5000 t P) was fully recycled in the domestic agri-food system, secondary P could completely substitute P imports in mineral fertilizers (4200 t P) plus partially substitute P imports in fodder or chemicals. This would reduce the TID indicator from 23% in the reference year to 15% in the scenario. If the recovered P was fully exported, the national import dependency would remain at the level of the reference year. This, of course, is only a hypothetical calculation, which illustrates the quantitative potentials of P in wastewater.

3.3. Scenario 3: Urine Separation

3.3.1. Scenario Background

Decentral alternatives to the incumbent centralized wastewater system have been explored for many years [64]. While the centralized structure comprising water-flushed toilets, sewers and wastewater treatment plants certainly has unquestionable benefits, e.g., in terms of hygiene or economies of scale, it also has various disadvantages such as high water consumption, large infrastructure requirements, and a mixture of household and industrial wastewaters hampering resource recovery or contamination of surface waters after the treatment process [5,65,66]. As a consequence, decentralized and distributed eco-sanitation systems, e.g., urine separation or compost toilets, could provide alternative approaches to centralized wastewater management—particularly in development areas, areas of new housing, and places with high density of excreta accumulation, e.g., airports, schools, shopping malls—and could facilitate P recovery and the creation of new P cycles [67,68].

In Switzerland, 98% of the population is connected to a public sewage network [69]. Thus, decentralized wastewater management is currently playing a marginal role. However, for more than 15 years, there have been efforts, e.g., pilot projects, towards more decentralized approaches including on-site wastewater treatment and urine separation [70]. Research projects such as NOVAQUATIS [36] and VUNA [37] at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) investigated different approaches to nutrient recovery from urine. As an outcome of the VUNA project, a market-ready liquid fertiliser "Aurin" was developed based on undiluted and treated urine (http://www.vuna.ch).

3.3.2. Scenario Description

In our scenario, 20% of the total urine in the subsystem *households & business* is collected separately, treated and sold as a secondary fertilizer to the subsystem *cultivation*. The scenario is based on an estimation by an expert from the field of urine separation, who considered a percentage of 20% of urine being collected and recycled as a challenging but a possible scenario for wastewater management in Switzerland [71].

3.3.3. Implications for Swiss P System

Separating and recycling 20% of total urine substitutes 15% of P imports via mineral fertilizer slightly reducing the TID indicator from 23% to 22% (Figure 3). In the scenario, a total of 700 t P accounting for 10% of P in wastewater is separated, while the remaining P in urine enters the sewage system mixed with faeces. Due to the reduced P content in wastewater, less P enters the subsystem *waste management*. As a consequence, less P is lost in landfills and cement after mono- or co-incineration of sewage sludge (−5%; −400 t P). Furthermore, P losses to surface water via WWTP effluents decrease by 11% (−100 t P). The PLW indicator remains constant at 90%, because urine separation already takes place in the subsystem *household & businesses* and therefore does not affect efficiencies in *waste management*.

4. Discussion

In this chapter, we compare the results of the three scenarios and embed them in the MLP. In doing so, we derive insights into the social, economic, institutional, and material dimensions of change processes towards a CE of P. Based on this, we spotlight three more general issues, i.e., scale, materiality, and governance, we consider relevant for researchers and practitioners in the wider context of the CE. Finally, we discuss our conceptual and methodological approach.

4.1. Comparative Analysis of the Three Scenarios

The three scenarios differ in their absolute and relative impact on the Swiss P system (Figure 4). A comparative analysis of the scenarios shows that, from an absolute perspective, scenarios 1 and 2 result in the quantitatively largest changes of flows and stocks. Scenario 1 particularly affects the agricultural sector reducing the overall P turnover in *animal husbandry* and *cultivation*; scenario 2 restructures P flows within and from *waste management*, reducing P losses in cement and landfills and producing new secondary P flows. Depending on the pathway of these secondary P flows, scenario 2 may additionally have a significant impact on import flows into domestic agriculture. Scenario 3 also changes P flows related to *waste management* but with less quantitative impact. In regards to the indicators TID, PEP, and PLW, scenario 2 has the biggest potential to reduce both Switzerland's P import dependency and P losses in the waste sector. It is important to note, however, that this is only the theoretical potential of scenario 2. We assume here that the secondary P recovered from sewage sludge (ashes) and meat and bone meal is completely recycled within the system boundaries, fully substituting P in mineral fertilizer imports and partially substituting P in fodder imports, e.g., feed additives. As explained in Section 3.2.2, this is doubtful due to the potential lack of demand for recovered P in Switzerland. Neither scenario 1 nor scenario 3 significantly affects TID and PLW. The PEP indicator remained constant at 94% in all three scenarios, since none of the scenarios included changes of agricultural practices related to P efficiency in soils.

There are two insights worth highlighting in the context of this comparative analysis. First, the analysis reveals that combining relative indicators with the analysis of absolute changes of P flows and stocks is crucial for gaining a comprehensive picture of the structure and dynamics of P systems. For instance, despite the significant absolute changes of agricultural P flows in scenario 1, the indicators are hardly affected compared to the reference year. Second, it is important to consider possible trade-offs between the different scenarios. The diffusion of urine separation technologies would reduce the amount of P in WWTPs rendering P recovery from wastewater or sewage sludge (ashes) less profitable. The same applies for trade-offs between scenario 1 and 2, where reduced amounts of animal by-products make the implementation of P recovery approaches from meat and bone meal less urgent. Besides these flow-specific quantitative trade-offs, more qualitative trade-offs emerge when, for instance, the successful implementation of the VVEA decreases incentives for reducing society's overall P requirements and the national P surplus in the first place, marginalizing sufficiency approaches such as dietary shifts. Furthermore, the economic dimension needs to be taken into account. For instance, different infrastructural waste management systems (central and decentral) operating at the same time lead to higher total operation and maintenance costs for society. Thus, when analysing, discussing, and planning future pathways of P use, these quantitative and qualitative interdependencies of the landscape, regime, and niche level need to be taken into account by both researchers and decision-makers.

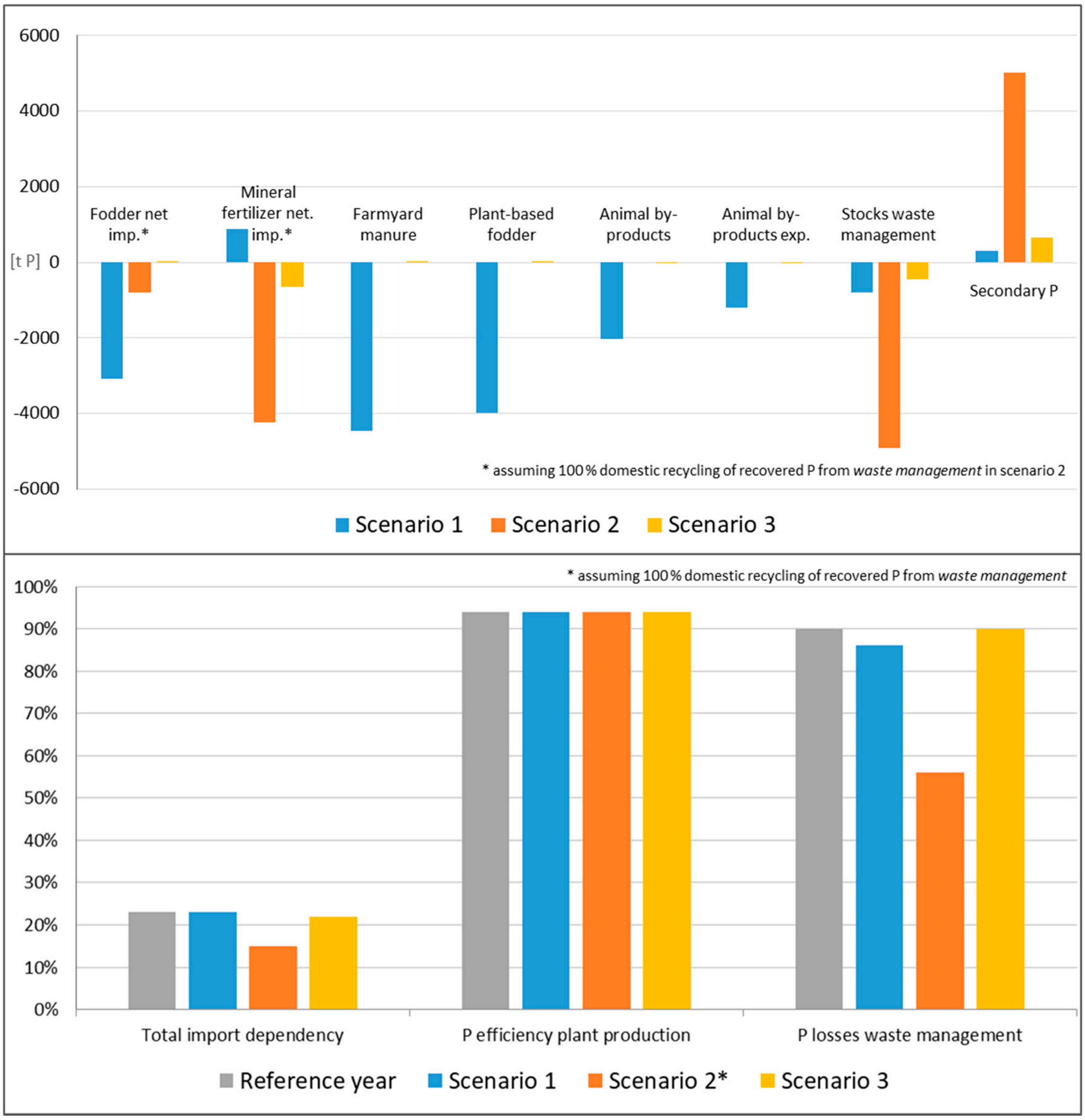

Figure 4. Changes (in t P) of selected annual P flows and stocks in the three scenarios compared to reference year 2015 (upper part) and indicator values of TID, PEP, and PLW in reference year and in the three scenarios (lower part) [stocks waste management = P to cement plant & landfills; secondary P = digestate & compost (scenario 1), secondary P from P recovery in *waste management* (scenario 2), and recycling fertilizer (scenario 3)].

4.2. Embedding the Scenarios in a Multi-Level Transition Context

4.2.1. Scenario 1: The Landscape Level

From a multi-level transition perspective, scenario 1 can be characterized as a process on the landscape level. Shifts in human diets are external framework conditions beyond the influence of actors within the Swiss P system leading to long-term changes in food consumption. The results of the scenario analysis illustrate that transitions in resource systems, e.g., towards a CE, are not isolated phenomena but are deeply embedded in external processes, which indirectly affect the dynamics of resource systems. This sheds light on the interdependencies between different fields of action related to human diets comprising health, environment, and resources. Trends and interventions in one sector, in our case health-driven initiatives towards a balanced human diet, lead to long-term changes in food consumption, resulting in altered P flow patterns on the household level with feedbacks to the agricultural system, foreign trade, waste management, and water bodies. In our scenario, all three systems, i.e., the health, resource, and ecological systems, would benefit from a shift to a balanced and healthy diet. First, human health improves due to more balanced food consumption, second, the system's overall demand for P decreases because of the reduction of the animal husbandry sector, contributing to a transition towards a CE of P and, third, risks of eutrophication decrease due to reduced P inputs to surface water.

It is important to note that shifts in human diets are one among many different possible context factors on the landscape level of a CE transition. McConville et al. [65] distinguished between social (e.g., dietary changes as in the scenario), technological (e.g., fundamental technological innovations), economic (e.g., fertilizer prices or shortages), environmental (e.g., environmental disasters), political (e.g., trade agreements), legal (e.g., regulations in other systems or on other scales), ethical (e.g., sustainability thinking), and demographic (e.g., urbanization) landscape factors, which all could potentially influence the transition towards a CE of P in Switzerland. Our scenario provides one example of how pressures from outside the Swiss P system can affect processes within the system.

4.2.2. Scenario 2: The Regime Level

The implementation of the VVEA, i.e., scenario 2, can be considered an incremental adaptation of the socio-technical setting of the incumbent waste system. By requiring P recovery from sewage sludge or sewage sludge ash, the VVEA draws on the existing infrastructural setting of a centralized wastewater treatment system including technologies and infrastructure such as WWTPs and mono-incineration plants. From an economic perspective, using this infrastructure could reduce implementation costs of the VVEA resulting in market-competitive secondary P products comprising both secondary feedstocks for P industries and recycling fertilisers for agriculture. Furthermore, the VVEA builds upon social institutions related to wastewater, i.e., citizens' behaviour, user preferences, and norms in terms of daily 'flush-and-forget' practices on the household level [72]. Thus, the implementation of the VVEA follows existing path dependencies of the waste system. From a transition perspective, this has two implications: First, radical innovations in the waste infrastructure have to overcome socio-technical barriers due to the highly institutionalized nature of the regime, whereas incremental adaptations are easier to conduct within the given socio-technical system structures. [73]. Second, by following incumbent pathways, the VVEA reproduces and strengthens the incumbent socio-material institutions creating social, e.g., governance-related, and material, e.g., infrastructural or technological, lock-ins and rendering alternative approaches of P recycling less probable in the future [20,74].

4.2.3. Scenario 3: The Niche Level

Decentralized sanitation approaches such as urine separation, i.e., scenario 3, can be considered niche innovations that provide alternatives to the incumbent centralized wastewater regime. Even though the results showed that the quantitative impact of the scenario in terms of the amounts of recycled P and substituted P imports is not as big as the impact of the implementation of the VVEA (mainly due to the lower diffusion of urine separation technologies in scenario 3 compared to the technology diffusion in scenario 2), urine separation represents the socio-technical character of transitions. It not only requires technical and infrastructural reconfigurations but also institutional changes of behavioural norms, e.g., to sit to urinate or related to flushing and toilet paper use (depending on the technology). Furthermore, the role of citizens in the wastewater system changes in the urine separation scenario. In contrast to current flush-and-forget practices, urine separation brings households, sanitation systems, and the agri-food system closer together. Particularly in community-based projects or areas of new housing, where urine is decentrally separated, collected, processed, and then marketed as a recycled fertilizer, citizens play a more active and immediate role in P recycling [5]. This strengthens the position of citizens in a CE and also contributes to re-establishing citizens' awareness for the societal, economic, and environmental value of human faeces.

However, the fact that a 20% diffusion of urine separation, as assumed in the scenario, is already considered an ambitious task by experts illustrates the challenges of niche innovations to diffuse in the face of incumbent socio-technical regimes. Due to the highly institutionalized nature of the centralized wastewater system, the implementation and up-scaling of niche innovations needs to overcome existing path dependencies and socio-technical lock-ins and is therefore a major challenge [75]. Furthermore, setting up a decentral infrastructure of waste management and P recycling is a cost-intensive task. In case decision-makers decided to foster these approaches, their implementation would require financial investment and long-term strategies for cost-efficient wastewater management.

4.3. General Insights into the Transition towards a CE of P

From the quantitative implications of our scenarios and their embeddedness in a multi-level system we can derive three more general insights for a transition towards a CE of P. In the following, we shortly discuss these issues, i.e., scale, materiality, and governance.

In terms of scale, our analysis shows that the way socio-technical approaches to P recycling in the context of a CE are discussed and assessed depends on the spatial scale of the analysis. From a national perspective, VVEA-based P recovery in scenario 2 does not necessarily result in national P cycles due to a potential lack of domestic markets. This is relevant for national policy-makers who bring forward the aim of reducing national import dependency when debating sustainable P management. If secondary P, e.g., secondary phosphoric acid, was exported and recycled in foreign P industries, then P recovery would not reduce Switzerland's P import dependency. It would create P cycles on an international, e.g., European, but not on a national level. As a result, national policy-makers could try to boost national demand for secondary P, e.g., by promoting the creation of production capacities in the P industry. However, from an international or global CE perspective, it is secondary whether P is recycled within Switzerland or abroad. Then, concepts of national import dependency and self-sufficiency fall short, because the CE of P is a global issue, where national P systems are embedded in global material, economic, social, and institutional interrelations. From this perspective, it is crucial to establish intact circular systems, where the recycling products meet the requirements of the relevant markets, e.g., in terms of the quality and price of the secondary P (products) compared to phosphate rock and mineral P fertilizer. This relates to what Gregson et al. [3] (p. 2) called the "economization of recycling" referring to the challenge of translating resource- or sustainability-based values and rationales behind CE initiatives to a tradable product. It is therefore important to embed the interpretation of results of SFAs, which are, by definition, conducted within clearly-defined system boundaries, in the broader spatial scales of e.g., global resource economies.

The issue of scale is closely linked to the role of materiality in CE transitions. P recovery technologies produce secondary P resources with very different material characteristics that affect or even determine future P pathways [54]. On the one hand, ash-based P recovery technologies produce materials such as secondary phosphoric acid (as it is planned in Zurich) that subsequently need to be further processed requiring industrial infrastructure, e.g., the fertilizer industry. On the other hand, secondary materials from sludge-based recovery technologies, e.g., dicalcium phosphate, can often be processed on-site after P recovery, e.g., via granulation to market-ready fertilizers, providing opportunities to more decentralized and small-scale approaches that are independent from industrial P systems. Thus, scale and materiality are two strongly interconnected dimensions of a CE, as recovery technologies produce different materialities that strengthen certain scales of a CE. As a result, some actors, economic sectors, and markets might benefit from a CE of P, whereas others are excluded from these value chains, because their specific requirements are not met by the secondary products. The challenge of economisation shows that P recovery is only the first step towards recycling secondary resources in a CE. Therefore, political decision-makers should take this into account by evaluating measures, e.g., financial incentives or quota systems for the use of secondary P in P industries and agriculture.

In terms of the governance of the CE, the case of P management in Switzerland provides insights into the different forms of governing transitions, i.e., top-down or bottom-up. On the one hand, the VVEA is a top-down policy measure that aims at reducing P losses by requiring P recovery from waste. As shown in our analysis, the implementation of the VVEA is going to significantly alter P flows within the incumbent socio-technical systems. On the other hand, niche innovations such as urine separation might have less quantitative impact depending on their diffusion (see scenario 3) but provide alternative systemic approaches to a CE. The fact that previous decentral sanitation projects were, to a large extent, driven bottom-up by citizens' initiatives or NGOs that operate outside the institutionalised system structures deliberately seeking new ways of dealing with human excreta [5], shows that there is a need for citizens to participate in designing and implementing a CE. Thus, it is important that CE policy and legislation leave space for socio-technical alternatives outside the incumbent regimes, which might have less effect from a quantitative resource perspective but have the potential to develop more radical approaches to future sustainability transitions. This could also involve transdisciplinary approaches that promote mutual learning processes between science, companies, and civil society in order to develop CE projects that meet the societal and economic requirements.

4.4. Conceptual and Methodological Insights

By combining SFA, scenario development and analysis, and a multi-level transition perspective, we were able to study both the quantitative implications of different scenarios for the Swiss P system and the socio-technical organization and political dynamics of the scenarios. As "not all the interesting data about material flows is of a quantitative nature" [76] (p. 2), our approach proved to be useful for going beyond the (theoretical) quantities of P flows and stocks in different scenarios. We gained insights into the overall socio-technical context and into how transition processes on different levels might contribute to a CE of P. Furthermore, integrating SFA in MLP studies made a methodological contribution to transition theory, which has been criticized for its lack of quantitative methods in empirical studies [77]. From a normative perspective, industrial ecology, which is the theoretical basis of SFA, on the one hand, is interested in studying how secondary material cycles can be created in order to decouple the use of primary resources from economic growth. Transition studies, on the other hand, investigate systemic change that entails both social and technical transformations of (circular) economies [78]. Thus, our approach allowed for both the material and the social dimension of the transformative processes of the resource economy.

5. Conclusions

In this study, we analysed the flow-specific quantitative implications of three socio-technical scenarios, i.e., (i) a shift to a balanced and healthy human diet, (ii) the implementation of P recovery from sewage sludge (ash) and meat and bone meal, and (iii) the diffusion of urine separation on a household level, for the Swiss P system. Based on the P system of the year 2015 provided in part 1 of our study, our results showed that while scenario 1 mainly affects the agricultural system by reducing the overall P throughput, scenario 2 significantly changes P use in waste management due to the decrease of P losses to landfills and cement plants and the increase in secondary P production. Scenario 3 showed little quantitative impact on the national P system. However, by embedding our quantitative results in a socio-technical transition context, we revealed that urine separation entails fundamental socio-technical shifts in the wastewater system, whereas P recovery from sewage sludge (ash) represents an incremental system adaptation. This combination of flow- and transition-oriented research provides thus more profound insights into the material, technological, economic, and social dimensions of a shift to a CE of P. Even though our analysis focused on P management in Switzerland, it is important to note that these national transition processes are embedded in a global resource economy. This is particularly relevant when analysing potential approaches to P recycling, as concepts of national self-sufficiency and the reduction of import dependency tend to fall short in the face of transnational material flows and resource markets.

Our analysis opened up space for future research. In the scenario analysis, we not only aimed at assessing the theoretical potential of certain developments, e.g., technological innovations or policy measures, in terms of their contribution to new P cycles but also tried to define future trajectories of the different secondary materials. However, due to limitations in current data on P recovery technologies, we were not always able to make assumptions or had to make simplified assumptions. In regards to scenario 2, provided that better data is available, future research could further refine the assumptions on P recovery technologies, their diffusion and the economisation of recovered P. Regarding scenario 1, future research could analyse the actual social, economic, and biophysical capacities of the Swiss agriculture to supply the assumed changes in food demand, i.e., more plant-based and less animal-based food, including more refined assumptions on changes in food imports and exports. Furthermore, since we focused only on the national scale, reframing the system boundaries in future analyses could provide insights into how CE-related measures affect different spatial scales from local to supranational and how these scales are connected via material flows.

Supplementary Materials: Additional information on indicators and scenario assumptions are available online at http://www.mdpi.com/2071-1050/10/6/1980/s1.

Author Contributions: CR.B. conceived the study. M.J. wrote large parts of the paper and, together with J.M., conducted the development and analysis of the scenarios. C.R.B. guided the analysis and writing process and revised the manuscript.

Funding: This research was funded by the Swiss Federal Office for the Environment, grant number 00.5035.P2I Q062-0017.

Acknowledgments: The authors wish to thank all experts from Eawag, Agroscope, Centravo AG, Zurich Office of Waste, Water, Energy and Air, Zurich University of Applied Sciences, Swiss Farmers' Union, Swiss Federal Office for the Environment and Swiss Federal Food Safety and Veterinary Office for their support during the data collection process. Furthermore, the authors thank the three anonymous reviewers for their valuable feedback.

Conflicts of Interest: The authors declare no conflict of interest.

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