IMPROVING INPUTS FOR ORGANIC FARMING

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1. Executive summary

The overall aim of WP3 of the RELACS project was to deliver recommendations on nutrient sources and recycling technologies acceptable for organic farming in order to substitute fertilizers and manures that are categorized as contentious. To this end, a survey on the current use of and need for external nutrient inputs was conducted in seven European countries, focusing on nitrogen (N), phosphorus (P) and potassium (K). Furthermore, using long-term experiments, different recycled fertilizers were evaluated with respect to fertilizer value, soil organic matter build-up and accumulation of potentially toxic elements. Knowledge on organic contaminants and associated risk assessment was gathered in a webinar series with key experts in the field. Acceptability and regulations were discussed in the webinar series as well as in further workshops with the organic sector. An economic analysis of recycled fertilizer use was performed in the frame of a case study. To enable organic farmer associations and authorities to assess regional nutrient demand and match it with available or future nutrient inputs, an online planning tool was developed and applied in different regions. Based on the outcomes of the different activities, we propose several key statements that synthesize the main findings and delineate a possible way forward with respect to ensuring a sustainable nutrient supply of organic agriculture in the future.

The survey of 71 European organic farms revealed high variation in P and K budgets, from deficits to substantial surpluses. Stockless farms tended to show greatest deficits. When reliance on biological N_2 fixation for N supply was very high (>80%), farm outputs were typically low and P and K budgets were mostly negative. Hence, additional N inputs to organic agriculture in Europe are needed to increase productivity, while inputs of P and K are required to prevent soil mining.

In the long-term field experiments, soil carbon (C) stocks were mostly increased by compost, and to a lesser degree by sewage sludge and straw-rich manure, while human urine, slurry and green manure did not affect soil C stocks. However, fertilizer that increased C stocks showed less benefits for productivity. The N fertilizer value of compost was dependent on the crop it was applied to, and a significant fraction of compost N applied was prone to losses since N mineralization continued outside the cropping season. Total N losses from the different fertilizers ranged between 35 and 55%, and nitrate leaching was the dominant loss pathway. The results highlight that each fertilizer has its advantages and disadvantages. Therefore, they should be utilized in mixtures and in accordance with their main benefits. For example, combining compost with additional N sources can contribute, to some extent, to increasing soil C stocks while minimizing nutrient imbalances and N losses. A field trial under conventional management showed that 20% of the typical mineral N dose could be replaced by sewage sludge without compromising yields and nutrient use efficiency or risking accumulation of potentially toxic elements, and with the additional benefit of adding organic matter to the soil, which may improve soil fertility, e.g. by improving aggregate stability. In all three long-term experiments, even moderately positive budgets of potentially toxic elements did not result in elevated levels of these elements in the soil or in crops, suggesting that all investigated fertilizers do not harm soil fertility with respect to elements such as zinc, cadmium or copper. Together, these findings imply that organic agriculture needs to use all available bioresources and combine them in appropriate ways in order to maximize their benefits while reducing negative effects on the environment.

The webinar series on organic contaminants in recycled fertilizers further substantiated the notion that heavy metals in agricultural soils originate mainly from feed supplements ending up in animal manure rather than from recycled fertilizers. With respect to organic and emerging contaminants, it was stated that the quality of sewage sludge in Europe has improved significantly over the past decades. Since most organic contaminants are bound in the soil, plant uptake is negligible and human exposure thus limited mainly to animal ingestion as the main transfer pathway, which can be prevented by simple management practices such as waiting periods after fertilizer application. Microplastics in soils originate mostly from tyre abrasion, followed by plastic mulches and recycled fertilizers, but have not shown harmful effects at typical concentrations found in soils today.

With respect to recycling technologies, the process of anaerobic digestion is suitable to recover nutrients from various organic wastes and shows much lower N losses than composting, while at the same time generating energy. The final product, however, has to be managed carefully since the N in it is prone to gaseous losses. With respect to recycling nutrients from human excreta, many technologies are under development to produce e.g. inorganic precipitates, ashes, slags and sorbents. Data from the CRUCIAL experiment suggests, however, that direct use of sewage sludge does not threaten soil quality. This finding needs to be further verified using long-term experiments in a range of situations.

We also evaluated the economic effects of replacing conventional manures in organic farming by recycled fertilizers and found that recycled fertilizers can replace conventional manures at the same price valuation, except that recycled fertilizers provide less potassium. The analysis revealed high shadow prices for all nutrients, especially for P and K. The on-farm utilization of the first available kilogram of off-farm nutrients increased the farm's contribution margin by up to 673 € kg-1 P, 81 € kg-1 K and 13 € kg-1 N, due to the possibility of yield increases with the use of external fertilizers. Since these shadow prices exceeded market prices for recycled fertilizers, omitting the use of external recycled fertilizers and thus limiting yields is not economically justified.

The online planning tool for calculating regional demand-supply balances for N, P and K identified a P deficit of 4 kg P/ha*year for organic farming in Switzerland. For the case of organic agriculture in Estonia, the deficit in P was even greater and there was also a K deficit. However, the estimates for Estonia need to be looked at critically, since the tool does not yet fully account for the fact that yields and nutrient demand are much lower in Estonia than in Switzerland. Nevertheless, to fill the current P and K deficit, a variety of nutrient sources should be used in combination. The tool is publicly available under nutrigap.fibl.org/.

A questionnaire answered by organic farmers from seven European countries revealed that nutrient deficits are generally not perceived as the main barrier for organic farming. While organic farmers are quite open towards recycled fertilizers and see the additional benefits of adding organic matter to the soil, their biggest concerns are that products might be contaminated with heavy metals, organic pollutants and plastic, or that they might be very costly. For sewage sludge products, societal acceptance needs to be guaranteed for organic farmers to accept such nutrient sources.

Based on the results and discussion during the four years of the RELACS project, we conclude that balanced inputs of all nutrients are needed to sustain productivity and soil fertility of organic farms. Since closing nutrient cycles is in line with organic principles, most recycled waste products could be suitable for organic agriculture, provided they fulfil quality criteria with respect to contaminants. Combinations of different inputs are recommended to maximize their benefits. Permitted nutrient inputs should fulfil clear criteria, such as originating from nutrient recycling, with low environmental impacts of the production process, and being safe and ideally beneficial for soil quality. Since most nutrient inputs have some drawbacks, a multi-criteria assessment needs to be developed by the organic sector, with weighting of individual aspects that enables use of many different nutrient sources in organic agriculture. If regular calculation of nutrient budgets at least for N and P would be mandatory for organic farms across Europe, nutrient imbalances and hence environmental side effects could be minimized, while increasing the productivity and nutrient efficiency of organic agriculture.

2. Introduction

The European Commission recently set a target of increasing the area of organic agriculture from 7.7% (2018) to 25 % of total farmland by 2030. Given the fact that considerable nutrient exports are unavoidable from organic farms that are linked to markets, organic farms will inevitably require a degree of import of nutrients to the farm to replace the nutrient sales of the farm. As a minimum, organic standards demand that nutrients removed from the system in harvest shall be replaced by biological nitrogen fixation (BNF), recycling and/or addition of mineral as well as organic materials and nutrients. Given the ambitious growth target set by the European Commission, it is imperative to understand current nutrient use patterns with a view to identifying future external nutrient supply needs and opportunities which can support the anticipated growth trajectory.

In WP3 of the RELACS project, we assessed the nutrient demand of organic farms across Europe as well as the availability of nutrient sources that might be used on organic farms in future. This report summarizes the main findings from WP3 by

1. summarizing the main findings from a survey on current use of and need for external nutrient inputs
2. demonstrating the benefits of various recycled fertilizers for soil quality
3. examining contaminants in recycled fertilizers as a potential barrier for use in organic agriculture
4. analysing economic implications of using recycled fertilizers
5. introducing an online tool to match available nutrient sources with nutrient needs
6. exploring the acceptability of recycled fertilizers to organic farmers

Based on these results, we then make recommendations regarding the development of future organic regulations. We present the "agreed positions" that were formulated during the European RELACS workshop in December 2021. We propose a definition of low solubility of mineral recycled P fertilizers. Finally, we propose a concept how to develop clear acceptance criteria based on a multi-criteria assessment of recycled nutrients, including a sound risk assessment.

3. Main results

3.1 Current use of and need for external nutrient inputs

Current on-farm soil fertility management practices, with a focus on external nutrient input use, were assessed for a sample of 71 organic farms across seven European countries. We utilized a farm-gate nutrient budget approach as a performance indicator of nutrient management practices and to quantify use of various external input types. Only the budgets for the main macronutrients N, P and K were calculated, and the input of N by BNF were estimated based on the areas under legumes using standard values of BNF.

Whilst on an aggregated level across all 71 farms, nitrogen (N) was in surplus and phosphorus (P) and potassium (K) were relatively balanced, it was evident that more than half of the surveyed farms had negative P and K budgets (Table 1). Variance between countries and also between farms in the studied countries was very high, especially for N and K. The highest N surpluses were detected in Switzerland, followed by North Germany and Denmark, while the lowest surplus was found in South Germany. For P, the highest surpluses were found in Italy and the biggest deficits in South Germany and Hungary. For K, three countries showed surpluses (Denmark, North Germany and Italy), while the highest deficits were found in Estonia and Hungary.

	N	P	K	N from BNF (%)	No. of farms
Denmark	35.9 ± 40.5	3.4 ± 7.7	18.5 ± 20.3	29.3 ± 13.8	7
Estonia	24.6 ± 13.2	-2.7 ± 1.5	-2.9 ± 3.2	97.4 ± 3.5	11
Hungary	16.2 ± 52.9	-3.0 ± 7.8	-3.1 ± 37.1	60.9 ± 40.1	10
UK	22.9 ± 64.1	-2.9 ± 7.3	-2.2 ± 13.0	77.7 ± 31.1	8
Italy	35.3 ± 65.6	10.7 ± 21.0	6.6 ± 90.1	51.9 ± 46.8	5
Switzerland	57.6 ± 25.4	0.2 ± 3.6	-1.4 ± 21.3	46.4 ± 19.7	10
Germany N	30.7 ± 45.5	-1.2± 7.7	12.6 ± 31.6	40.5 ± 29.3	10
Germany S	6.0 ± 20.1	-3.9 ± 4.2	-2.1 ± 23.1	69.9 ± 26.6	10
All farms	28.1 ± 42.5	-0.8 ± 8.4	2.4 ± 31.8	61.1 ± 33.9	71

Table 1: Mean values and standard deviations of nutrient budgets for N, P and K for each case country and averaged across the full sample (in kg ha-1 year-1) and for nitrogen proportion of inflow from biological nitrogen fixation (BNF) (%).

The reliance on BNF for the supply of N to the farms also differed highly among countries and farms, ranging from 0–100% of N supply through legumes. While Estonian farms relied on average over 97% on BNF for their N supply, inventoried farms in Denmark had a reliance on average of just below 30%. Where reliance on BNF was high, ensuring supply of P and K was identified as a challenge (Figure 1).

The differences in farming intensification were also reflected in the provisioning of external inputs. For example, Danish farms acquired on average 68 kg N from outside sources from sources less than 20 km away, whereas Hungarian farms acquired on average 16 kg N from sources most often more than 150 km away. Across all farms, the average proportion of nitrogen sourced from conventional manure was 16%, again with considerable variation across countries (northern Germany 4%–Hungary 43%).

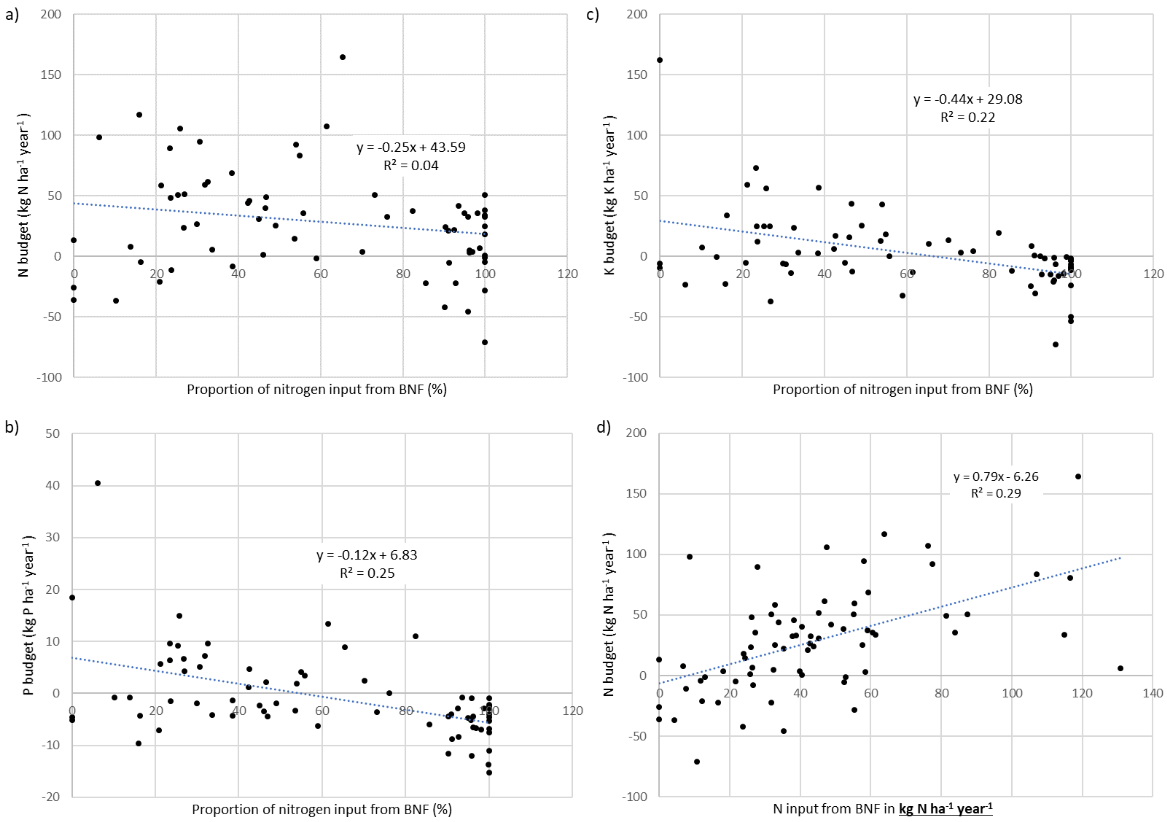


Figure 1: Correlations of nitrogen (a), phosphorus (b) and potassium (c) budgets for all farms versus proportion of N inputs derived from biological nitrogen fixation, 4 (d) is a correlation of the N budget versus the amount of N input per farm in kg N ha-1. Data presented are three year averaged values for each farm across eight case areas.

The average N output was 55 kg N ha^{-1}, while the median value was 44 kg N ha^{-1} across all countries (Figure 2). In the more intensive production found in Denmark, Switzerland and northern Germany, where farms generally use substantial amounts of inputs, the average N output was 79 kg N ha^{-1}, while the median value was 74 kg N ha^{-1}. If access to external nutrient supply would diminish as a result of future regulation (for example of 'contentious inputs'), so would the outputs from the more intensively managed farms. If the new target set for organic farming by the European Commission in the Farm to Fork strategy is to be realized, it is not trivial to strive for a higher farm output, and an increasing land-use efficiency. This will develop in a time where climate change will stress the food systems, and where there is a general wish to increase and protect undisturbed natural areas.

Expert input from the respective countries generally aligned with the trends in the data. Regarding the sustainability of nutrient supply, a synthesis of expert opinion identified key areas of concern. The first is that there is currently an undersupply of external fertilizer inputs that are permitted in organic systems, particularly for stockless holdings. Secondly, the purchase of external inputs to balance nutrient needs is costly for farmers, and farmers therefore rely strongly on ensuring enough legumes in the rotation to meet soil fertility needs (for N). However, focusing on ensuring a sufficient N supply can cause P and K deficiency. Thirdly, the quest for reliable supplies of 'organic' sources of sufficient nitrogen in balance with other limiting nutrients (e.g., from composts, vinasse, seaweed, digestates) is fraught with difficulty because these sources are highly variable (in terms of nutrient content) and difficult to manage as their effect on soil function and nutrient release processes is hard to predict, and they can result in oversupply of some nutrients.

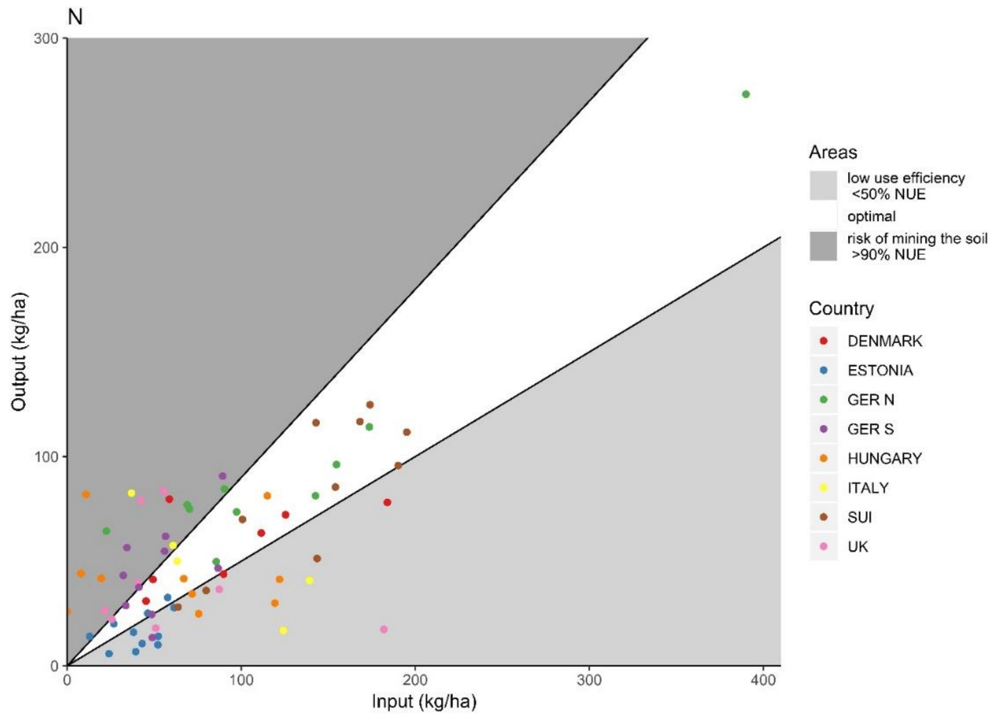


Figure 2: Nitrogen input-output graphs for 71 organic farms included in the study. Inputs and outputs are given in kg ha-1 year-1. The upper line represents a 90% nitrogen use efficiency (NUE) and the lower line a 50% NUE.

3.2 Short and longer-term benefits of recycled fertilizers with respect to soil quality

In order to evaluate the short- and long-term effects of recycled fertilizers on soil fertility, data from three long-term field trials at different location were analysed. Thereby the focus was on the yield effect, nutrient supply and imbalances, soil carbon and nitrogen dynamics as well as the risk of accumulation of potentially toxic elements (PTE) in the soil due to application of recycled fertilizers. The field trials were located at different sites throughout central and northern Europe and dealt with different recycled fertilizers. The first trial was established in 1997 in Stuttgart, Germany, on an experimental farm run by the University of Hohenheim. It investigated the effect of different household waste compost application, solely and in combination with mineral nitrogen fertilization, on soil fertility, soil PTE accumulation and yields. The second trial was located in Speyer, Germany, and was run by VDLUFA Speyer. It was established in 1981 and investigates the effect of different sewage sludge applications. The third trial, CRUCIAL, is located near Copenhagen, Denmark, and compares the effect of different recycled fertilizers (sewage sludge, household waste compost, stored human urine) to the effect of animal manures with variant straw contents (deep bedding, manure, slurry), mineral fertilization and unfertilized controls on soil fertility (Magid 2006). It was established in 2002 on an experimental farm run by the University of Copenhagen. In order to take a closer look at the N cycle, the soil-plant-atmosphere model DAISY was calibrated using the data from CRUCIAL and the N and C cycles were simulated.

Each investigated trial and model simulation highlighted different aspects of the implication of using recycled fertilizers. The data from the Hohenheim “biocompost” showed that through compost application, soil organic matter, extractable P and K and total N concentration and thus N mineralization increased. This lead to higher yields, N concentration in the product and N offtakes due to compost applications (Figure 3). However, the short-term agronomic effects (< 5 years) of compost application (yield, N availability) accounted for approx. 80% of the total effects, while the remaining 20% are achieved on a longer perspective. The yield effect was highly dependent on the applied compost dose and the crop it was applied to. Due to a better synchronisation of crop demand and mineralization pattern, a crop with a longer growing season in late summer, such as maize, can utilize the compost N better than crops with a short growing season in summer. In winter wheat about 35-30% of the total N mineralization occurred outside of the growing season and was therefore lost. This is also reflected in the input-output efficiency of compost N, which was significantly higher in maize than in spring barley or winter wheat. In addition, the results showed that using compost alone to fulfil crop N demand will result in surpluses of other nutrients, especially P. However, combining compost with additional N sources will balance out these nutrient imbalances and secure stable yield levels. Compost applications are also related to the risk of introducing PTE into the system. For a compost application rate of 100 kg N ha^{-1} $year^{-1}$ a surplus of 292 g Cu ha^{-1} $year^{-1}$, 68 g Ni ha^{-1} $year^{-1}$, and 654 g Zn ha^{-1} $year^{-1}$ was observed. Yet, this did not lead to a significant increase in soil or plant concentration for theses PTE after 21 years of application.

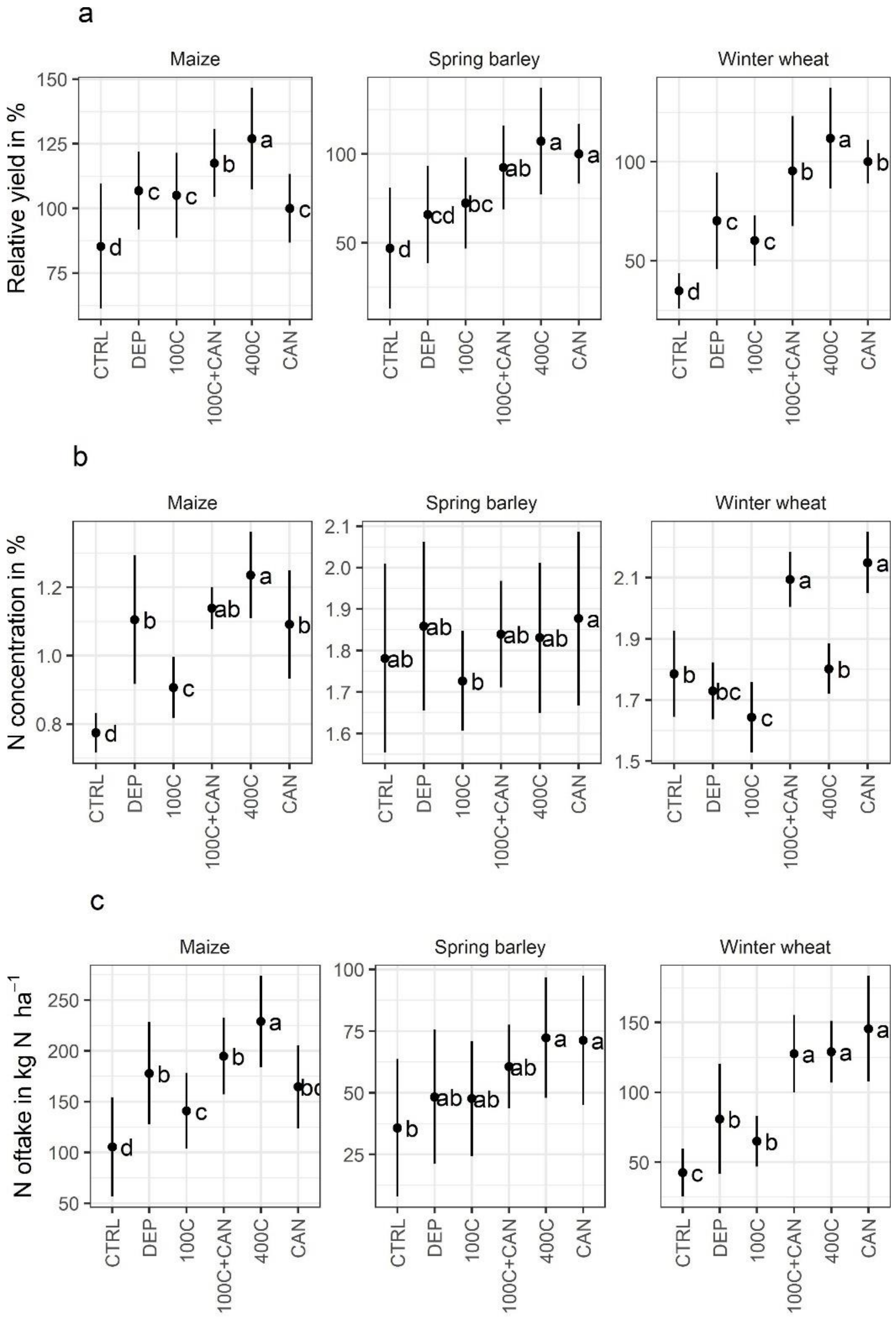


Figure 3: a) Mean yield of maize (n= 144), spring barley (n=72) and winter wheat (n= 96) from 2003-2019 relative to the mean yield of maize (35.40 t FW ha-1), spring barley (4.26 t FW ha-1) and winter wheat (8.10 t fresh matter ha-1) of the CAN treatment. b) N concentration in % of the harvested product (whole crop for maize, grain for spring barley and winter wheat). Dots represent the mean and the lines the standard deviation. Letters indicate significant differences within treatments (α = 0.05 Tukey-Test). CTRL: unfertilized control, DEP: 400 kg N ha-1 yr-1 compost in 1998-2003 and afterwards unfertilized, 100C: 100 kg N ha-1 yr-1 compost, 100C+CAN: 100C with additional mineral fertilization, 400C 400 kg N ha-1 yr-1 compost, CAN: mineral N.

The long-term field trial on the use of sewage sludge run by VDLUFA emphasizes the fertilizer value of long-term application of sewage sludge (nearly 40 years) in combination with additional N sources. The long-term sewage sludge application mainly influences the P supply, while the N fertilizer effects accounted only for 0-20% of the total supplied N. Additionally, it provides the benefit of an increase in organic matter in the soil, while no undesirable PTE concentrations were detected in the crops and soil.

The CRUCIAL trial investigates different recycled fertilizers (household waste compost (CH), sewage sludge (S), stored human urine (HU)), cattle manures (deep litter (DL) and slurry (CS)), mineral fertilization (NPK) and two unfertilized controls (unfertilized (U) and green manure (GM)). The trial also includes three accelerated treatments with an approximately three times higher application rate for compost (CHA), sewage sludge (SA) and cattle manure (CMA). The fertilizer application were dosed so that the maximal allowed available N amount as determined by the Danish legislation was applied, yet this results in highly different total N amounts (Table 2). The use of the soil-plant-atmosphere model DAISY made it also possible to assess the fate of N added to the system by the different fertilizers. Results from the trial show that with respect to yield effect, N offtake, N efficiency (Table 2) and nutrient budget (Figure 4), human urine performed similar to the mineral treatment while compost and sewage sludge performed similar to cattle deep litter and manure, with the exception of a higher N recovery rate for sewage sludge. Compost, sewage sludge and the animal manures also showed high nutrient surpluses, especially for P. Further, they showed high net surpluses of Cu, Cd, and Zn. However, these net surpluses were not reflected in the soil and plant concentrations. López-Rayo et al. (2016) investigated the soil PTE levels in the CRUCIAL trial in 2013, and only found an increase in soil Cu concentration in CHA and in soil Zn concentration for S, SA, CH, and CHA. However, these measured values of up to 33 mg Cu kg^{-1} and 92 mg Zn kg^{-1} are far below soil concentration that are considered as critical (Tóth et al. 2016). They also investigated the plant PTE concentrations and only found an increased Cd concentration for the sewage sludge treatment in oats and an increased Zn concentration in pea shoots. Yet again, these values were below the EU limits and the increase in Zn could even be regarded as a positive side effect, since Zn is an essential element in plant and human nutrition.

Treatment	Input	Losses	Output	Soil change	% Losses	% soil change	% Output
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	% input	% input	% input
CH	409	185	123	101	45	25	30
CHA	1158	636	149	375	55	32	13
S	215	100	106	6	47	3	49
SA	507	281	138	84	55	17	27
HU	189	99	106	-15	52	-8	56
DL	368	139	115	114	38	31	31
CMA	363	125	101	139	34	38	28
CS	132	62	78	-5	47	-4	60
NPK	143	69	98	-22	48	-16	68
U	20	31	47	-54	157	-275	238
GM	98	43	61	-7	44	-7	62

Table 2: Average yearly nitrogen input, losses, output, and soil nitrogen storage change (positive values mean an increase) and the proportion of losses, output and soil N change in relation to the total input. (Input: fertilizer, deposition, seeds, fixated nitrogen; losses: leaching, volatilization, surface loss, N_2 from denitrification, N_2O from nitrification and denitrification; output: harvested products; soil N change: organic & mineral soil N storage change)

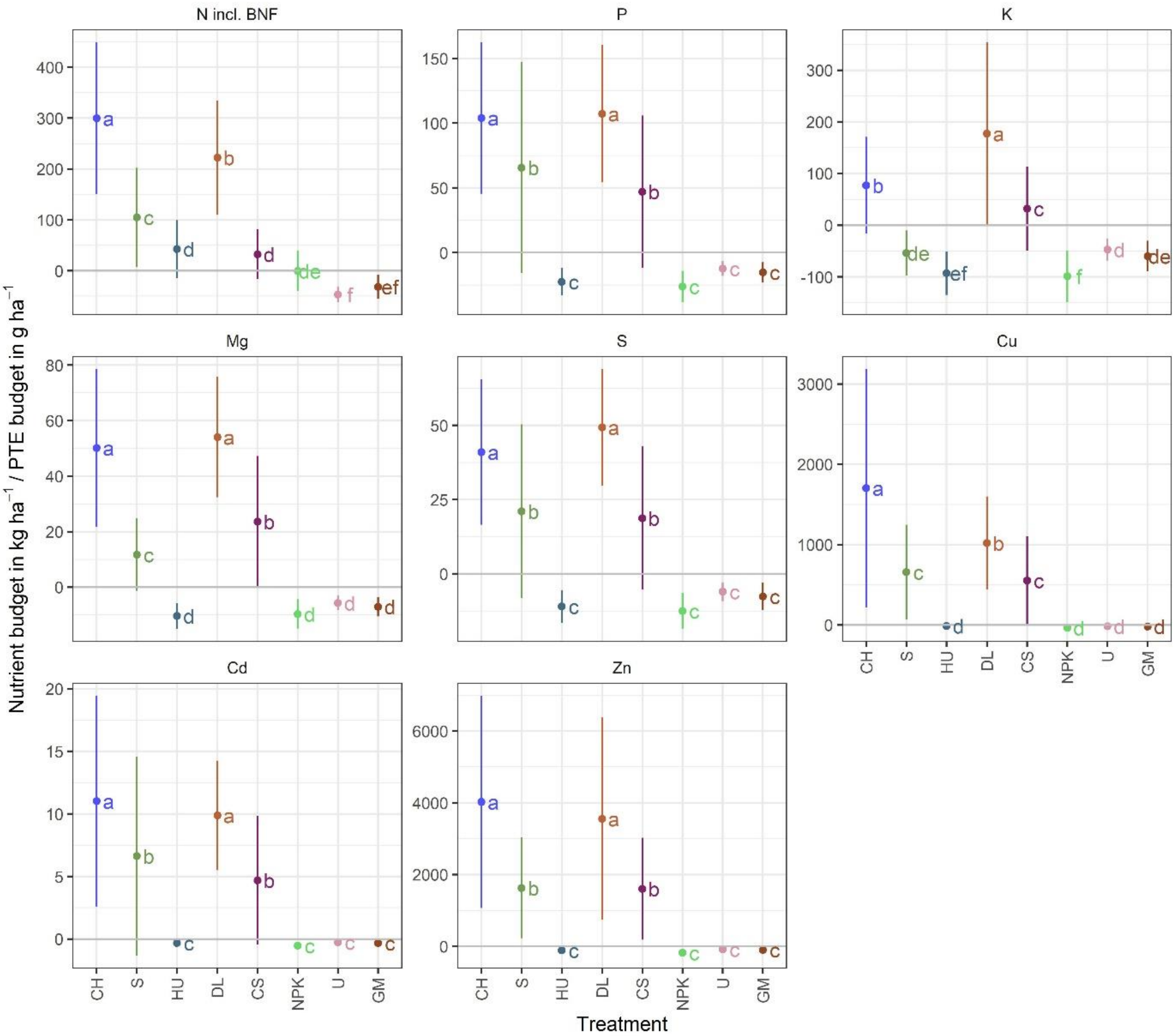
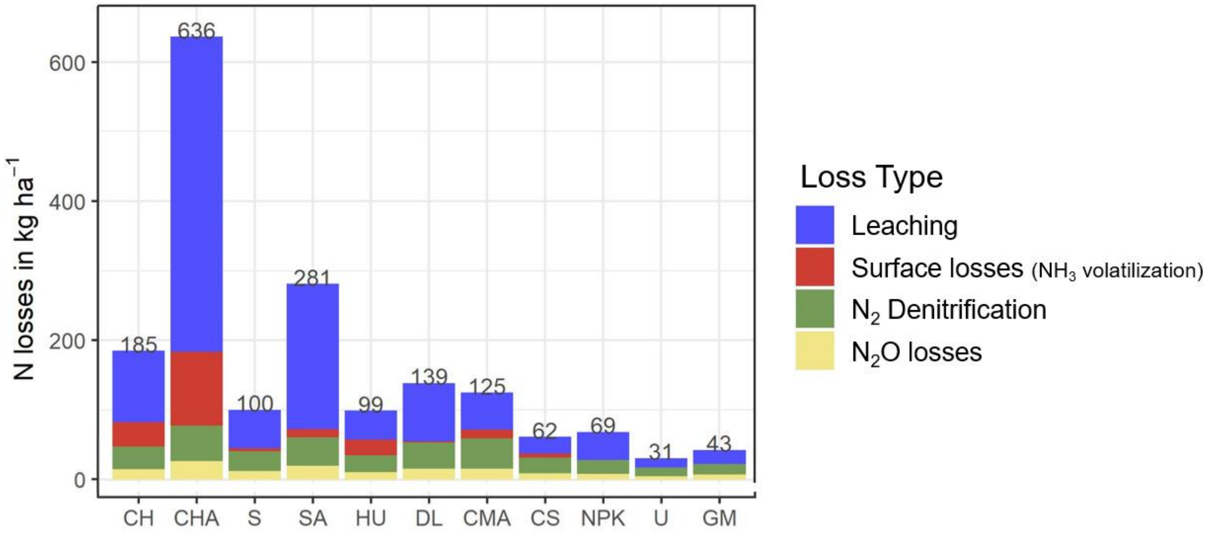


Figure 4: Input-output budgets for the main nutrients in kg ha^{-1} year^{-1} (for N including biological nitrogen fixation (BNF), P, K, Mg, S) and potentially toxic elements (PTE) in g ha^{-1} (Cu, Cd, Zn). Shown are the means (dots) and the standard deviation (lines). The letters show significant differences among the treatments (α=0.05).

The model exercise with DAISY revealed that about 34-55% of the total N inputs were lost (Table 2). The highest losses were found for the accelerated treatments due to high N application rates, which exceeded the crop demand. The main loss pathway was nitrate leaching. Additionally, human urine showed high losses through ammonia volatilization, which explains it relative high proportion of losses. These volatile losses could however be counteracted by an optimised application technique e.g. through soil injection.

Furthermore, there was a trade-off between N recovery in the outputs and soil N change (Table 2). Compost and straw-rich animal manures showed the lowest N output recovery, but about 25-38% of the N input was stored in the soil and increased not only the total soil N concentration but also resulted in an significant increase in soil organic matter. Over the trial period soil carbon increased by about 47 Mg ha^{-1} in the CH, by 119 Mg ha^{-1} in the CHA, by 23 Mg ha^{-1} in the SA, by 25 Mg ha^{-1} in the DL and by 30 Mg ha^{-1} in the CMA treatment. Contrastingly, treatments with a negative soil N change (HU, CS, NPK, U, GM) showed only small changes in soil carbon (-0.6 Mg ha^{-1} for HU, 0.8 Mg ha^{-1} for HU, 1.2 Mg ha^{-1} for NPK, -1.1 Mg ha^{-1} for U and -0.2 Mg ha^{-1} for GM).

The results from the CRUCIAL trial highlight that each fertilizer has its advantages and disadvantages. Therefore, they should be utilized in mixtures and accordingly to their strength.



Average annual N losses throughout the trial duration with different types of loss (leaching, surface losses (mostly NH_3 volatilization and runoff), N_2 production from denitrification and N_2O emissions). Numbers represent the total N loss in kg ha^{-1}.

3.3 Contaminants in recycled fertilizers

In March and April 2021, a webinar series entitled "Organic contaminants in recycled fertilizers and their fate in soil-plant systems" and consisting of five webinars of about 2 hours each was organized by FiBL and University of Copenhagen in the frame of the RELACS project. It attracted about 120 participants with affiliations in academia (universities or research institutes), in the organic sector, and in companies, ministries and other institutions. The series with 18 invited speakers started with presentations on the contaminants (heavy metals, organic contaminants, microplastics, pathogens and antibiotic resistance genes). It then continued with presentations on different approaches to recycle nutrients from various waste streams, i.e. anaerobic digestion, biorefinery and nutrient recovery from human excreta. In the last session, the impact of different recycling technologies on the environment was addressed via life-cycle assessment, and the legal base and process for acceptance of inputs for EU organic production was introduced.

The main findings presented are summarized below:

1. Heavy metals: Zn, Cu and Cd are three main metals of concern in agricultural soils, the net input comes from animal manure (feed supplements) and phosphate fertilisers; however, the Cd mass balance is close to steady state. Zn and Cu originate mainly from mineral feed supplements. Plant availability is more important to consider than total metal concentrations in soil.
2. Organic and emerging contaminants: Sewage sludge quality has greatly improved over the past decades, at least in Europe, partly because production of many chemical compounds has moved away from Europe. The behaviour of most organic contaminants in the soil-plant-system limits human exposure due to negligible plant uptake. Animal ingestion is the main transfer pathway to human diet but can be prevented by simple management practices. Consequently, no immediate risks of organic contaminants in sewage sludge have been identified.
3. Microplastics in soils originate from tyre abrasion, plastic mulches and from recycled fertilizers. At the concentrations found in soils today, no harmful effects have been observed.

4. Anaerobic digestion has advantages over composting, i.e. reduces N losses during treatment and generates energy. The fertilizer product (=digestates) has a high water content and the N is prone to losses upon application in the field.
5. Management of human excreta starts with the type of toilets used, resulting in yellowwater, brown-/blackwater and/or sewage. The main product types are solutions, inorganic precipitates, ashes, slags and sorbents, and organic sorbents and solids. Data from the CRUCIAL experiment suggests that direct use of sewage sludge does not threaten soil quality.

3.4 Economic analysis

In the context of a master thesis, the economic applicability of recycled fertilizers in organic farming was investigated. For this purpose, a model for organic farms was created on the basis of linear programming and German data. This model was first used to simulate the use of recycled and conventional fertilizers in different farm types under different fertilization scenarios. Furthermore, the on-farm utilization of the externally supplied nutrients nitrogen, phosphorus and potassium was investigated for three defined farm types with the help of the model. The farm types differ with respect to livestock (stockless or dairy farming) and crops (Table 3). Different fertilization scenarios were simulated. First a scenario without the use of external fertilizers was initially assumed. In the further scenarios, the use of conventional manures and recycled fertilizers was simulated. Among the recycled fertilizers were compost, digestates, sewage sludge, bone meal, and struvite available to replace the conventional manures (cattle manure, pig manure, chicken manure) and phosphate rock. Both the conventional (except phosphate rock) and recycled fertilizers were priced according to a price derived from the prices of the pure nutrients. For the recycled fertilizers, the valuation price was also increased, thereby determining the maximum price at which use in organic farming would still occur.

I a)	Stockless arable farm with a cereal legumes crop rotation
I b)	Stockless arable farm with cereal, legumes and root crops rotation
II a)	Dairy farm with 40 milking cows (0.4 AU ha^{-1}) with a cereal legumes crop rotation
II b)	Dairy farm with 40 milking cows (0.4 AU ha^{-1}) with cereal, legume and root crop rotation

Table 3: Description of the four different farm types that were investigated.

It was evaluated how recycled fertilizers could economically replace the conventional manures in organic farming and what price would still economically justify a use of the recycled fertilizers. In addition, the effects on the contribution margin and the nutrient and humus balance were examined. In further evaluations, the monetary on-farm utilization of the external nutrients nitrogen, phosphorus and potassium as well as the crops cultivated in the process are shown.

The results show that recycled fertilizers can replace conventional manures at the same price valuation. However, a small contribution margin discount is associated with the fact that the recycled fertilizers provides less potassium and have to resort to the more expensive substitute patent potash. When replacing conventional manures with recycled phosphorus fertilizers, potash supply should therefore not be neglected. Currently, the nutrient phosphorus in particular is at the centre of scientific discussions. Table 4 shows the results for an arable farm with a cereal-legume crop rotation as an example.

Among the recycled fertilizers, digestates from biogas plants and composts are preferably selected in all farm types, but more in root crop farms, due to the potassium content. In contrast, struvites, which are primarily phosphorus fertilizers, are used to meet phosphorus needs even when prices are high in root crop rotations. Ultimately, from a purely economic perspective, the recycled fertilizer that can provide the nutrient most cheaply will be used. Whether the simple processes of anaerobic digestion and composting or the recovery processes of phosphorus from sewage sludge are more competitive depends on the production technology as well as regional market conditions. For phosphorus recovery technologies from sewage sludge in particular, it remains to be seen how they will evolve and which process can recycle the nutrients most economically.

With a price for recycled fertilizers that also corresponds to a multiple of the valuation price, fertilization with recycled fertilizers and an associated increase in yield is still more favourable than abandonment in external fertilization. In the extreme case, struvite with a 68-fold valuation price amounting to 33,500 € mt^{-1} is still worth using in potato cultivation in a dairy farm system. The on-farm recycling analyses also support the use of recycled fertilizers at high prices. The results show that on-farm utilization for the first available off-farm phosphorus reaches a value of 673 € kg^{-1} P (Table 5). For potassium, a lower but still high level of 80.7 € kg^{-1} K is reached and for nitrogen, the on-farm recovery is the lowest with a maximum of 13 € kg^{-1}. Thus, on-farm utilization for the first available external nutrients exceeds the market prices for nutrients from recycled manure and an economic added value for organic farms can be created. Limiting yields due to a limited use of external fertilizers can therefore not be justified from an economic perspective and can only be attributed to a limited availability of external fertilizers. Approval of additional fertilizers is therefore necessary. In particular, sewage sludge and the fertilizers derived from it could contribute to a sustainable nutrient supply after approval for organic farming and at the same time increase the contribution margins in organic farming.

Farm type	Fertilizer scenario	Quantity of external fertilizer	Multiple of valuation price	Contribution margin in €	N (kg) / ha	P (kg) / ha	K (kg) / ha	Humus-C (kg) / ha	Spelt (ha)	Winter wheat (ha)	Winter rye (ha)	Faba beans (ha)	Peas (ha)	Clover grass - N-fixation (ha)	Clover grass - hay (ha)	Clover grass - silage (ha)
I.a)	**A)**	No external fertilizer	n.a.	60.552	0	-11	-20	-116	20	20	7	19		14		
	B)	287 mt cattle manure 343 mt liquid pig manure 15 dt rock phosphat	1	99.305	12	0	0	-2	20	20	7	13	20			
	C.1)	171 mt liquid digestates 403 mt compost 49 mt sewage sludge	1	99.046	24	0	0	415	20	20	7	13	20			
	C.2)	104 mt liquid digestates 451 mt compost 49 mt sewage sludge	3,55	77.285	25	0	0	466	20	20	7	20	13			
	C.2)	127 dt patent potassium 73 dt Struvit	7,1	60.422	0	0	0	-83	20	20	7	14		19		
	D.1)	1262 mt compost	1	96.956	54	0	17	1466	20	20	7	3	20		10	
	D.2)	1140 mt compost	4,2	60.879	50	0	32	1266	20	20	20	13	20			
	D.1)	1931 mt liquid digestates	1	90.175	77	0	46	129	20	20	7	13	20			
	D.2)	1923 mt liquid digestates	2,7	60.591	71	0	46	110	20	20	20	13	20			
	D.1)	145 dt patent potassium 155 mt sewage sludge	1	91.525	14	12	0	-51	20	20	7	20	13			
	D.2)	137 dt patent potassium 82 mt sewage sludge	6,4	60.512	7	0	0	-65	20	20	7	20	4	9		
	D.1)	135 dt patent potassium 213 dt bone meal	1	84.503	2	5	0	-85	20	20	7	20		13		
	D.2)	131 dt patent potassium 155 dt bone meal	6,8	60.309	2	0	0	-83	20	20	7	18		15		
	D.1)	127 dt patent potassium 73 dt Struvit	1	82.312	0	0	0	-83	20	20	7	14		19		
	D.2)	127 dt patent potassium 73 dt Struvit	7,1	60.422	0	0	0	-83	20	20	7	14		19		
Valuation price		Liquid cattle manure 11,37€ / mt Cattle manure 10,42 € / mt Liquid pig manure 14,21 € / mt Poultry manure 30,80 € / mt						Liquid household digestates 9,02 € / mt Green waste compost 9,73 € / mt Sewage sludge 62,54 € / mt Bone meal 26,95 € / dt Struvit - Stuttgarter Process 49,37 € / dt								

Table 4: Contribution margin, nutrient balance and cultivated crops for different fertilization scenarios for an arable farm with a cereal-legume based crop rotation)

Farm type	Nutrient	Available external P in kg	Shadow price in €	Spelt (ha)	Winter wheat (ha)	Winter barley (ha)	Winter rye (ha)	Spring barley (ha)	Oats (ha)	Faba beans (ha)	Peas (ha)	Potatoes (ha)	Sugar beets (ha)	Carrots (ha)	Clover grass - N-fixation (ha)	Clover grass - hay (ha)	Clover grass - silage (ha)
I.a)	P	2118	0,0	20	20	7		20								33	
		1906 (-10 %)	4,9	20	20		7	20			13					20	
		1588 (-25 %)	10,1	20	20		7	20		12	20					1	
		1059 (-50 %)	115,3	20	20	6 (0%)	20 (0%)	1 (0%)							33 (0%)		
		925 (-56 %)	129,0	20 (0%)	20 (0%)	7 (0%)	20 (0%)								33 (0%)		
I.b)	P	1993	0,0	20	20	20						20		20			
		1793 (-10 %)	85,7	20	20		9					20		20	11		
		1494 (-25 %)	103,2	20	12							20		20	28		
		996 (-50 %)	495,8	20 (0%)			1 (0%)		20 (0%)			20		6 (0%)	33		
		870 (-56 %)	673,2	20 (0%)			7 (0%)		20 (0%)			20 (0%)			33		
II.a)	P	582	0,0	20	20	7		20								8	25
		523 (-10 %)	4,9	20	20		7	20			3					5	25
		436 (-25 %)	74,9	20	20		20	7			8						25
		291 (50 %)	96,3	20	20		20 (8%)	7							8		25
		146 (-75 %)	129,0	20 (27%)	20 (0%)	7 (0%)	20								4 (0%)		29 (0%)
		75 (-87 %)	129,0	20 (0%)	20 (0%)	7 (0%)	20 (0%)								4 (0%)		29 (0%)
II.b)	P	714	0,0	15	20							20		20			25
		642 (-10 %)	103,2	20	12							20		20	3		25
		535 (-25 %)	115,3	20	7							20		20	8		25
		357 (-50 %)	342,9	20 (0%)					7 (0%)			20		20 (18%)	8		25
		179 (-75 %)	466,7	17 (0%)					20 (0%)			20		10 (0%)	8		25
		20 (-97 %)	673,2	20 (0%)			7 (0%)	20 (0%)				20 (0%)			8		25

Table 5: Shadow price for phosphorus as well as cultivated crops with increasing scarcity of phosphorus in the four different farm types. The brackets show the yield increase of the respective crop when no or a partial yield increase was realized.

3.5 NutriGap

To facilitate regional planning of nutrient supply to organic farms, we developed an online planning tool entitled NutriGap. This tool allows organic farmer associations and authorities to calculate a demand-supply-balance for nitrogen, phosphorus and potassium on a regional basis, either in order to evaluate current nutrient supply and improve it by balanced sourcing of external nutrient inputs, or to examine different scenarios of growing areas under organic production. The tool is publicly available under nutrigap.fibl.org/.

For organic farming in Switzerland at present (data from the year 2017), NutriGap clearly identified a deficit in P supply of 4 kg P/ha*year which needs to be addressed by increasing the use of recycled fertilizers in organic agriculture in Switzerland. If the area under organic cereal production in Switzerland would double without any change in animal production, the N surplus would decrease and the P and K deficits increase slightly. Overall, however, organic agriculture in Switzerland appeared to be quite well buffered due to the high numbers of animals.

For organic farming in Estonia, data on the main crops covering 94% of all organic agricultural area was entered as well as data on all organically kept animals (cattle, other ruminants, pigs and poultry). The interim balance was slightly positive for N after accounting for atmospheric deposition and biological nitrogen fixation, but clearly negative for P and K. This is in accordance with the findings in D3.1. However, the nutrient demand is probably overestimated due to the Swiss data for yields and nutrient demand stored in the tool, which are likely higher than in Estonia. A future development of the tool should integrate more specific data for organic agriculture in climatic regions or countries.

3.6 Questionnaire on the acceptability of recycled fertilizers

The views of 83 organic farmers in six European Countries (Italy (ITA), Germany (DEU), United Kingdom (UK), Hungary (HUN), Estonia (EST), Denmark (DNK), Switzerland (CH)) regarding the acceptability of recycled fertilizers for organic agriculture were collected during the visits to organic farms for the survey to assess the current demand for and use of external nutrient inputs. The main questions concerned reasons for converting to organic farming, main obstacles with organic management practices, willingness to use certain recycled fertilizer products, and the reasoning behind their decision.

In the first two questions, farmers were asked to rate reasons for organic farming (Figure 5) and problems with organic management (Figure 6) from 1-5, where 1 is not important, 2 is slightly important, 3 is moderately important, 4 is important and 5 is very important. The results show that farmers mostly converted to organic farming to protect the environment, the soil and their health and to produce a better product, while economic reasons were of less importance (higher prices, lower input costs, market stability).

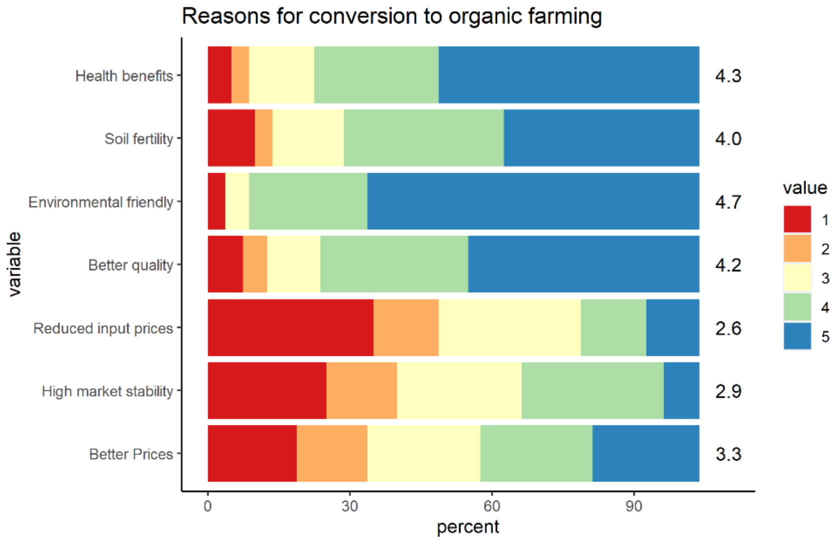


Figure 5: Rating of 83 organic farmers of reasons for organic farming on a scale from 1-5, where 1 is not important, 2 is slightly important, 3 is moderately important, 4 is important and 5 is very important. The numbers behind the bars represent the mean.

The obstacles of organic management were generally considered of less importance (Figure 6) than the reasons for conversion to organic farming (Figure 5). Weeds were considered the most severe problem in organic farming, followed by low yields. Low nutrient availability was the third important obstacle, with over 50% rating it of moderate to high importance, closely followed by labour shortage, pests and diseases. Low prices and low quality of the product were the least important problems, with over a third of the interviewed farmers claiming that they are not important at all.

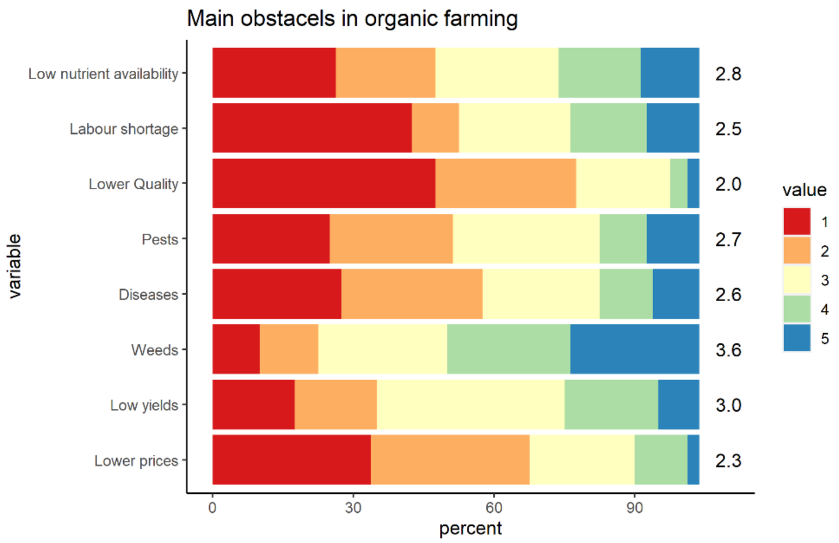


Figure 6: Rating of 83 organic farmers of the main obstacles of organic management on a scale from 1-5, where 1 is not important, 2 is slightly important, 3 is moderately important, 4 is important and 5 is very important. The numbers behind the bars represent the mean.

Although low nutrient availability was not rated as an important obstacle in organic farming, most of the farms claimed that they rely on external inputs to fulfil their nutrient needs (Table 6). This differed, however, between countries. In EST, for example, 91% of the farmers said they rely on external nutrients, while in the UK, DNK, and ITA more farmers said they do not rely on external nutrients. In the UK, there were more farms with animal production in the sample than on average, which may have a lower reliance on external nutrients due to higher possibilities of internal nutrient recycling through the animals. In ITA, there were many farms with orchard crops (like olives) which need less nutrient inputs than conventional arable crops. In EST, DEU and HUN, on the other hand, there were mainly stockless farms which do not have many options of internal nutrient recycling of nutrients.

Country	Rely on external nutrients	Do not rely on external nutrients
CHE	60	40
DEU	70	30
DNK	43	57
EST	91	9
HUN	70	30
ITA	41	59
UK	38	63
Average	60	40

Table 6: Percentage of farmers who claim that they (would) need external nutrient inputs to fulfil the farm nutrient demand.

The general acceptance of recycled fertilizers was very high, with 80% of all farmers willing to use recycled fertilizers on their farm. The farmers were also asked about their acceptance of the following specific fertilizers: compost from household waste as well as compost from green waste (e.g. cuttings and prunings), anaerobic digestates, spent mushroom substrate, sewage sludge as well as sewage sludge products (e.g. struvites or ashes) and animal products (e.g. horn meal, blood meal, hair meal). The highest acceptance overall was for spent mushroom substrate and green waste, with about 74% of farmers willing to use those nutrient inputs on their own farm (Figure 7). Animal products were accepted by 60% of farmers, and digestates and household waste compost by around 50%. Sewage sludge and sewage sludge products showed the lowest acceptance. However, the perception of recycled fertilizers differed among countries. The acceptance of sewage sludge, for example, was more than twice as high in DNK and UK as in the other countries. Further, in HUN there was a relatively low acceptance of digestates but a high acceptance of household waste compost.

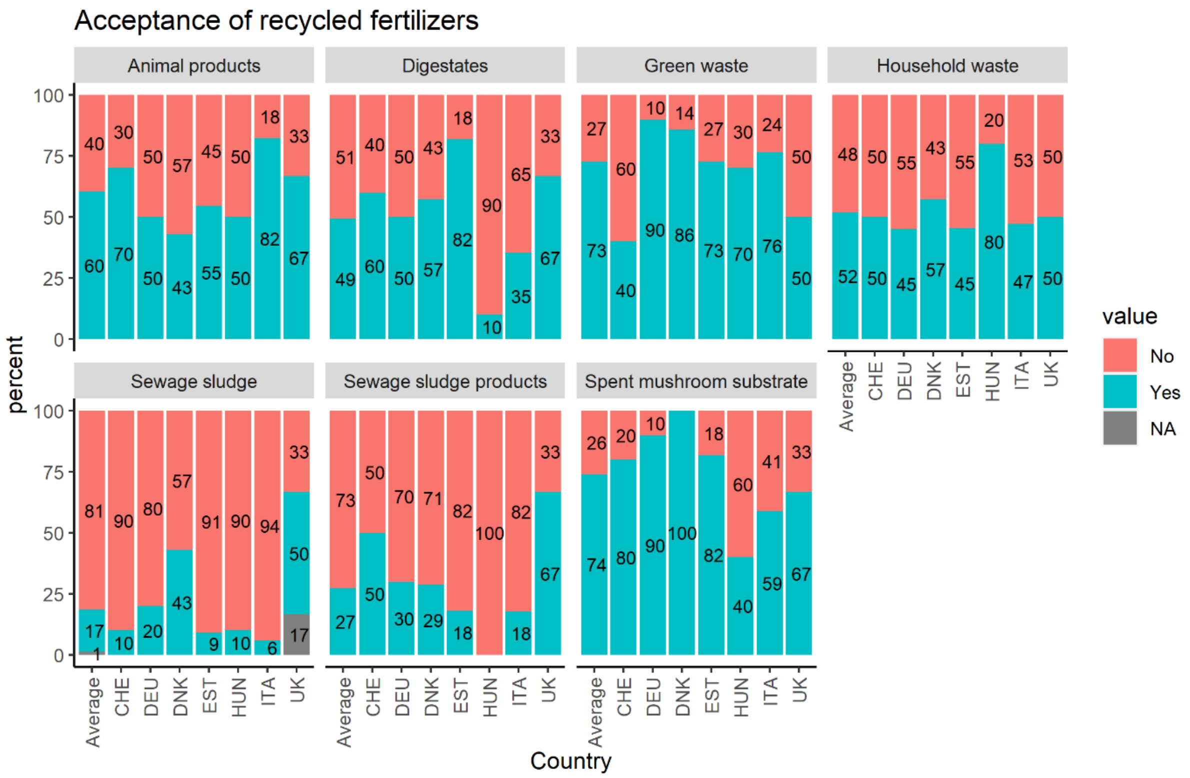


Figure 7: Acceptance of recycled fertilizers shown as percentage of farmers willing to use the recycled fertilizers within their own farm. (N=81 farmers, 2 farmers from UK did not want to answer the questionnaire)

All different fertilizers were considered positive in that they aid in closing the nutrient cycle and working towards a more circular economy. Apart from that, the reason for or against using a certain recycled fertilizer differed between the different inputs (Figure 8). The biggest concern was that the products might be contaminated, except for animal products where the high cost was the number one concern. Mostly potentially toxic elements (also known as heavy metals) were mentioned as contaminants, but also organic pollutants. For household compost, contamination with plastic was also of high concern. For the sewage sludge and sewage sludge products a distinctive concern of societal acceptance was frequently mentioned and not seen for the other fertilizers. A positive aspect for composts, digestates and spent mushroom substrate was the addition of organic matter to the soil.

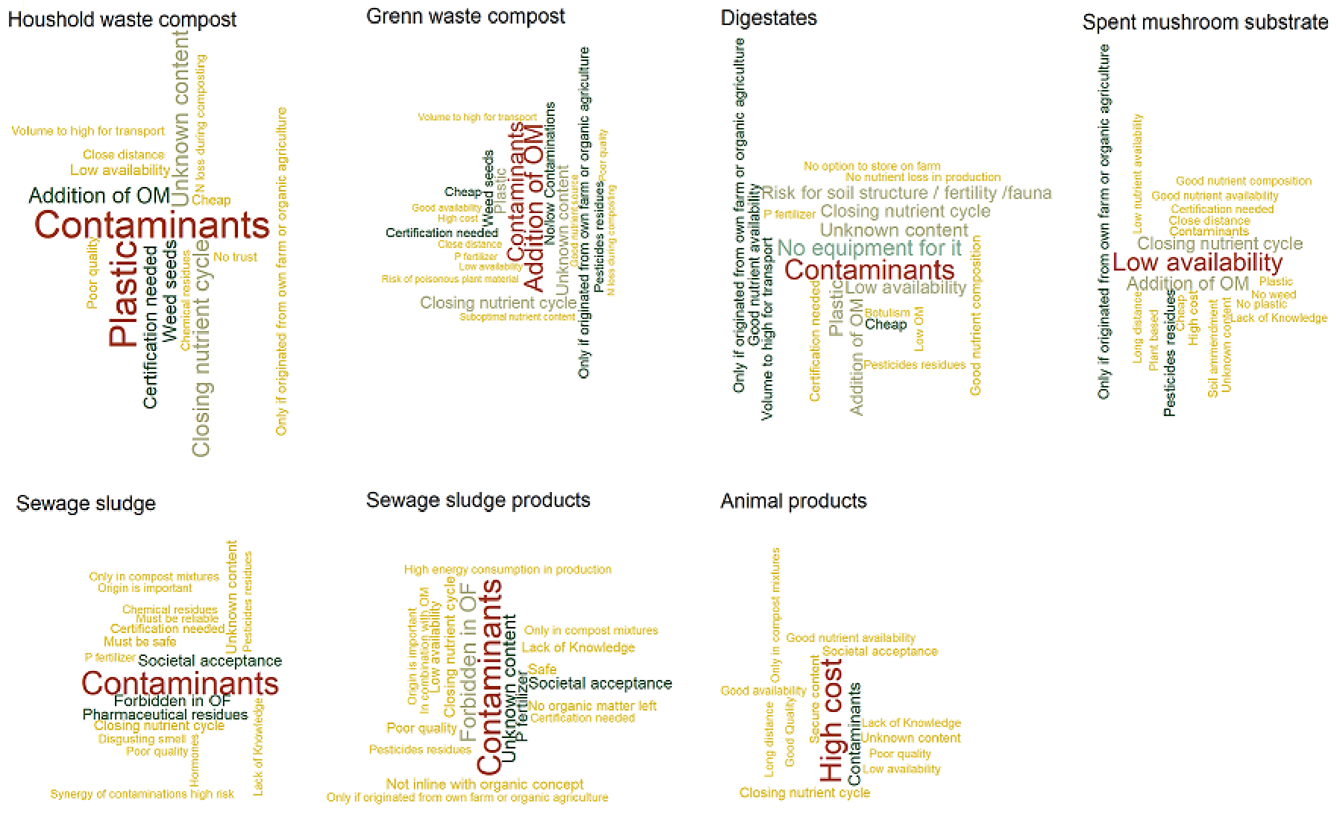


Figure 8: Bullet points showing the reasons for and against the use of different recycled fertilizers. The size and the colour both represent the frequency with which they were mentioned (the bigger the word, the more it was mentioned & yellow<light green<green<red)

Protecting the environment and caring for human health is of high importance to many organic farmers, but they also experience nutrient shortages and rely on external nutrient supplies to fulfil the nutrient demands of their farm. Therefore, they are very careful when it comes to choosing fertilizer inputs. These must match the demand of the farm as well as the organic farming principles. The results of our study show, that most farmers are willing to use recycled fertilizers from urban and food industry waste streams. However, the acceptance differs depending on the type of fertilizer and region. In general, composts, spent mushroom substrate, digestates as well as animal products have a higher acceptance than sewage sludge or sewage sludge products, where there is a concern of societal acceptance. Otherwise, the risk of contaminations was the main concern towards recycled fertilizers, with the exception of animal products, where the high costs for it was the main obstacle. One positive aspect that was mentioned for all fertilizers is that they are a good option for closing the nutrient cycle and going towards a circular economy.

4. Recommendations

4.1 Agreed positions

During the RELACS European Workshop, the following statements were discussed and agreed upon among participants (mainly scientists and organic farmers' associations).

To retain a high farm productivity, stockless arable and low animal intensive farms are highly dependent on external sources of N besides biological nitrogen fixation.

To ensure a sufficient nutrient supply, and avoid soil nutrient depletion, recycling of societal waste streams needs to be further developed and researched. The Organic Agriculture rules regulating inputs need development alongside with this.

It is necessary to focus on balanced long-term supply of all nutrients and not exclusively on P. In some situations, P is the most limiting nutrient in the long term. Currently we do not have appropriate and legal P fertilisers in sufficient amounts.

Recycling is in line with organic principles. It is recognized that societal and food industry waste streams have improved in quality as contaminant levels have decreased, and it is necessary to widen the access to recycled waste products, based on quality criteria.

With respect to heavy metals in agricultural soils, Zn and Cu are of concern and originate mainly from mineral feed supplements ending up in animal manure.

Most organic contaminants are bound in soil, leading to negligible plant uptake. Direct animal ingestion of organic contaminants from recycled fertilizers can be prevented by management practices.

Low water-solubility of many recycled P fertilizers makes them suitable for organic agriculture (see 4.2).

The acceptability of mineral N sources from recycling needs to be further discussed in the organic sector.

4.2 P solubility in recycled fertilizers

Current organic regulations limit the use of mineral fertilisers to materials of low solubility (Art 5(g) (iii) of Reg. 2018/848). For new mineral recycled P fertilisers, a definition of "low solubility" is needed. Therefore, we screened the available literature to examine the forms of P present in recycled P fertilizers, which are often mixtures of different P minerals (Kratz *et al.*, 2019). We reviewed the solubility of these different P forms in different extractants, showing that solubility of the pure minerals in water is typically either high (> 85%) or very low (<5%). Limiting the proportion of water-soluble P in recycled fertilizers to max. 25% allows the use of many recycled fertilizers that show excellent plant P availability such as struvite, but excludes recycled P fertilizers that contain mostly Mono- or Diammonium phosphate, Monocalciumphosphate, Mono- or Dipotassium phosphate and Disodiumphosphate.

4.3 Developing a multi-criteria assessment of recycled fertilizers

Rather than looking mainly at the fertilizer characteristics (e.g. solubility), regulations could address mainly potentially harmful components (e. g. pollutants) as well as the production process of a given recycled P fertilizer. For example, only the use of recycled substrates and chemicals could be allowed, and energy consumption could be limited to technical needs (e.g. mixing, grinding) rather than being used for chemical processes. Such an approach would phase out mineral N fertilizers produced by the Haber-Bosch-process, but allow to some extent to solubilize ashes by the use of sulphuric acid obtained in processes like soap production that must be landfilled otherwise. This would result in a fertilizer which contains at least two nutrients (P and S) that are often scarce in organic farming.

Hence, we suggest that the selection of external nutrient sources to be permitted in organic agriculture should be based on clear criteria. We propose the following principles:

1. Before sourcing external fertilizers, farm-internal recycling and/or cooperation between organic farms should be maximized.
2. External fertilizers should originate from nutrient recycling (rather than mining finite resources or synthesise N from the air via the energy-intensive Haber Bosch process).
3. The fertilizer production process should have a low environmental impact (as indicated by standard LCA).
4. The fertilizer should not harm the soil and ideally be beneficial for soil quality.

These principles are similar to the assessment developed in the Improve-P project (**Error! Reference ource not found.**), which was however limited to P sources and did not define the weight of each aspect. Hence, it is necessary to make the criteria applicable to all nutrient sources and establish thresholds, beyond which a given aspect is not fulfilled.

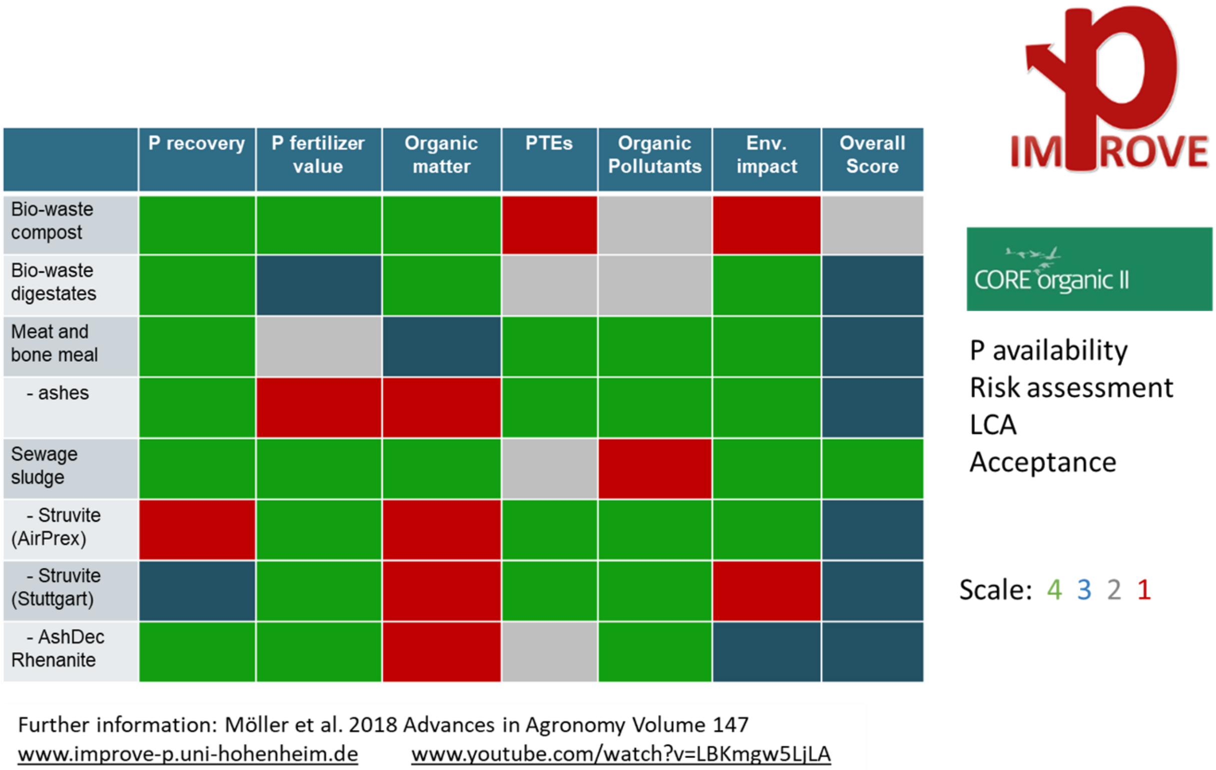


Table 7: Multi-criteria assessment of recycled P fertilizers

In addition to developing a comprehensive multi-criteria assessment, organic regulations should be revised to make the annual calculation of farm N and P budgets mandatory in all countries. This would decrease nutrient imbalances in organic farming which often result in nutrient losses to the environment.

6. Conclusions

The different activities in WP3 of the RELACS project have clearly demonstrated the need of organic farms across Europe for balanced supply of nitrogen, phosphorus and potassium as well as the general openness of organic farmers towards recycled nutrient inputs, provided that they fulfil quality criteria, especially with respect to contaminants. Analysis of several long-term experiments as well as expert consultation has shown that cadmium, copper and zinc are the potentially toxic elements that could be of concern for agricultural soils. While cadmium budgets are generally balanced, hence no accumulation is occurring, copper and zinc tend to accumulate in soils. However, they originate mostly from feed supplements rather than from recycled fertilizers. With respect to organic contaminants, an improved understanding of their fate in the soil-plant system is needed. Based on our results, it seems that the ability of soils to immobilise and/or degrade contaminants is typically underestimated. Together, this means that most recycled organic wastes can likely be considered safe for use in agriculture, at least in Europe where contaminant levels in waste streams have decreased considerably during the last decades. The organic sector needs to develop a matrix of requirements for nutrient inputs to organic agriculture, which should be based on the principles of closing nutrient cycles and preventing harmful effects on the soil as well as the environment. This implies accepting trade-offs between different fertilizer properties and considering the overall environmental impact of the production process rather than limiting the assessment to specific characteristics of the final fertilizer product. Together with a mandatory requirement for balanced nutrient supply on organic farms in order to minimize nutrient losses to the environment, this will assure the productivity and sustainability of organic agriculture.

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