A note on sewage sludge - risk assessments and fertilization value

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Background

In 2012 the Coordination Program Network of European Transnational Research in Organic Food and Farming Systems called for research on sustainable and efficient management of phosphorus and use of secondary fertilizers within organic agriculture. Recognizing that the mineral resources of natural phosphorous world-wide (suitable for extraction) are expected to meet requirements for the next 100 years only, a special focus on efficient use of existing P from alternative sources such as processed farm fertilizers, municipal waste and waste from the food industry, was highlighted among other points of interest. Oelofse et al. (in press) discuss the implications of phasing out conventional nutrient supply in organic agriculture which has been emphasized by a decision by Danish Organic farmers to ban import of manure and straw from conventional farms by 2021. Alternative strategies to ensure nutrient supply will require a tapestry of small solutions. One element of this tapestry is to review the volume and type of nutrient sources available in alternative, non-farm organic waste streams, and consider their suitability for use in organic systems. One lesson emerging from this study is that it will be impossible to cover the need for P fertilization in non-dairy farms without resorting to reuse of sewage sludge, which is in line with the ideas of one of the forefathers of organic agriculture, Sir Albert Howard, was a very strong proponent of the recycling of organic waste (Heckman J, 2006). Oelofse et al. (in press) assessed that a decision to allow the use of sewage sludge in one form or other will require a discussion of principles, and is perhaps an issue which requires discussion within organic agriculture about whether this can be a considered a breach of principles, a compromise or a fulfillment of the organic ideology of working with closed cycles. In the following sections a number of recent studies of risk related to agricultural use of sewage sludge are reviewed, as a contribution to the discussion of potential for use in organic agriculture. Furthermore a very tentative assessment of the fertilization value of sewage sludge and its derived products is developed.

Introduction

Sewage sludge contains numerous substances, and new substances continuously enter waste streams, while others are phased out. Therefore it is pertinent to regularly assess and contribute to knowledge about the risks associated with agricultural use of modern sewage sludge for fertilization purposes. In the light of the substantial body of knowledge available today there is no factual basis for rejecting the agricultural use of European municipal sewage sludge. The chemical quality of sludge in Western countries has constantly improved and concentrations of potentially harmful and persistent organic compounds have decreased to near background levels. Never the less, agricultural use is prohibited some places in Europe based on the precautionary principle.

The precautionary principle ('Better safe than sorry') has some inherent problems, as discussed by Cass Sunstein in 'Laws of Fear' Sunstein (2005). First and foremost, law makers tend to focus our on the public’s immediate concerns (e.g. stories in the press that are blown out of proportion), as in the recent Danish case of PCBs in sewage sludge. Secondly, there is a tendency to focus on the "worst-case" scenario, leading to probability neglect. Finally, systemic impacts of the precautionary principle are routinely ignored. In case of sewage sludge, the decision not to use it will have unintended consequences in terms of increased greenhouse gas emissions from sludge incineration, and possible environmental degradation, e.g. due to mining in order to obtain phosphorus and long-term use of a finite resource (phosphorus). Incinerated sludge can be processed industrially to ensure recovery and recycling P, which addresses perceptions of risk related to agricultural use of sludge, but has associated environmental and economic costs. Incineration causes losses of other nutrients, in addition to carbon that will have a long residence time in the soil after application, thus saving CO_2 emissions.

Under EU law, the precautionary principle may invoked where urgent measures are necessary in view of a possible danger to human, animal or plant health, or to protect the environment, when the scientific data does not permit a comprehensive assessment of risks. It cannot be used as a pretext for protectionist measures. The precautionary principle is mainly used where there is a danger to public health, e.g. used to stop of products that may cause a health hazard. Thus, according to the EU, there can be no question of merely taking a negative attitude to risk. The risk must be weighed against the benefits of allowing the given product.

As will be apparent from the summarized reviews below, there is a large amount of data, which allows a comprehensive assessment of risk. While a complete risk assessment cannot be made, since there are some questions that still need attention, (i.e. emerging contaminants that need addressing), there is an overwhelming body of evidence indicating that recycling of sewage sludge on farmland is not constrained by concentrations of organic contaminants found in contemporary sewage sludges. Furthermore the consensus view therefore is that there appears to be no scientific rationale for including numerical limits on organic contaminants in quality assurance systems for the agricultural use of sewage sludge. Heavy metals in soil should remain limited, but in view of ever lower concentrations measured in sludge, the sludge could be used again and again in the same place for a very long period before the concentration in the soil will even approach the ecotoxicogical limits. There will continue to be a need to examine the impact of new contaminants entering the 'chemical food chain'. Moreover, risks associated with agricultural use of other organic fertilizers that may contain substances that are environmentally undesirable but added feed to promote growth of livestock should be considered. If the risks related to use of e.g. pig or chicken manure are much higher than that of using sewage sludge it would seem out of proportion to incinerate sludge based on environmental concern. However such comprehensive assessments have not been made to the best of our knowledge.

A number of issues that are not likely to be substantial for agricultural use, requires further study and include: (i) the effects of chlorinated paraffins in the food chain and on human health, (ii) risk assessment of the plasticizer di (2-ethylhexyl) phthalate, a bulk chemical present in large amounts of sludge, (iii) the microbiological risk assessment of antibiotic-resistant microorganisms in sewage sludge and sludge-affected farmland, and (iv) the potential importance of personal-care products (eg triclosan), pharmaceuticals and endocrine disrupting substances in sludge on land and human health. Currently, a Danish study found that (v) emerging and poorly elucidated polyflourinated compounds may be at the limit of what the EU recommends in its guidelines under the REACH program under the assumption of long-term use of sludge with the highest Danish measured concentrations. It would therefore be appropriate to examine the presence of those compounds and actual effect further, in order to reduce the uncertainty that exists about its influence. This could be done in the Copenhagen University long-term trials using sewage sludge and other waste products.

The risk of new and existing industrial chemicals is calculated vis-à-vis expected long-term concentration in farmland on the basis of relative worst-case inputs. Depending on the information available on the effects of the substance in soil the REACH risk assessment procedure assigns a minimum margin between the expected concentration and the concentration at which there is a measurable adverse effect to exclude a risk. If the data material is sparse and incomplete, uncertainty is higher, and therefore required a safety margin of at least 1000 is applied, while the safety margin for a complete dataset (ecotoxicological long-term studies from three trophic levels) is reduced to 10. Therefore, it may be necessary to make in-depth studies if a highly conservative safety margin of a given substance can be exceeded in worst case scenarioes.

The substances retained in the sewage sludge are generally less soluble. The most toxic substances (e.g. tetrachlorinated-p-dioxin) cannot be detected in the sludge. The undesirable substances in sludge are affected by a number of mechanisms for delivery that inhibits or prevents transfer to crops and the food chain in general, including: (i) rapid evaporation and loss to the atmosphere for some substances, (ii) the rapid biodegradation and minimal or no persistence for others, (iii) strong adsorption of persistent connections to the earth, and (iv) minimal or no uptake by plants and grazing animals.

A tentative assessment of the fertilizer value of P sewage sludge

There are a number of studies of the effect of P in the sludge, which show that the fertilization value is quite similar to P in manure. At Copenhagen University's Long-term waste utilization experiments 10 years of use of sludge and manure yield the same proportionate effect on plant available soil phosphorus (see section below).

There are some reports on how different sludge treatment processes affect the P availability/P fertilizer value of sludge, but they are not in line with each other, and use different methods to measure availability. Thus anaerobic digestion has been found to increase and decrease P availability. Dewatering has been reported to decrease, while thermal drying has been reported to decrease or have no effect on P availability. Incineration has been reported to decrease availability, and our own work in progress indicates a marked drop in P solubility in both water, HCl and NaOH after incineration.

There have been no systematic studies of how P effect of sludge varies with how sludge is flocculated, but it would be appropriate to do this, as it is likely to have an impact. There have been a few inquiries from farmers who believe they have observed a negative effect - which might be due to a relatively high dose of iron or aluminum salts in the flocculation. However, this is probably the exception – since an increasing proportion of the sludge produced in DK, is used in agriculture.

It may seem obvious that the effect of P in a readily soluble fertilizer may be better than that of a more slowly soluble fertilizer, such as sludge or manure, but this is not necessarily true. Plants have different possibilities for influencing the solubility of P, but generally they can only do it in the rhizosphere environment, which represents a very small part of the total soil volume growth layer (about 5%). Moreover, it is well established that a significant portion of the P plants absorb not readily soluble. Therefore, there is a great advantage in ensuring that there is a high concentration of P in the vicinity of the emerging plants, which explains the very high effect of placing a small quantity of P (e.g., 5 kg ha-1) to a crop sown in the spring. Therefore it could be worth investigating the effect of placed pelletized sludge, placed near the emerging seeds and thereby be able to get a better effect. Broad cast compound fertilizer P has a more modest effect, since it relatively quickly dissolves and becomes part of the total adsorbed P pool in the plow layer, where it maintains soil fertility. Current efforts are underway to make P and micronutrient fertilizers that do not react with the surrounding soil, but only release nutrients on demand from growing plants.

Copenhagen University's Long-term trial using sewage sludge and other waste products

In 2002 the Department of Plant and Environmental Sciences, established a long-term field trial with different waste biomass, including: sewage sludge, composted / anaerobically digested household waste, human urine and a number of commonly used organic fertilizers. This trial is maintained to ensure that it is possible to continuously research beneficial and potentially harmful effects on soil or crop quality from utilizing waste products in agriculture. One main aim is thus to provide a basis for the ongoing assessment of recycling of organic residues from urban to rural areas.

At this writing (April 2013) we have applied a total amount equivalent to more than 100 years of normal dose of sewage sludge and urban waste compost on accelerated application treatments. Accelerated treatments have been introduced in order to approach heavy metal concentrations to the level recommended as cut-off values based on ecotox assessments. The sludge comes from Avedøre sewage center that currently does not comply with the criteria for agricultural use, to establish a Danish 'worst-case'. Very large differences in soil quality have developed across the different treatments. An archive of frozen samples of the waste biomass each from each year has been established to enable the tracing of new substances of interest. The studies made so far do not indicate adverse effects of sewage sludge (Poulsen, 2013a) but shows as indicated above that sludge from Avedøre has the same P effect as manure based on the relative increase in Olsen P values compared to the increase in soil total P. It is shown that after an input corresponding to approx. 60 years of normal supply of sewage sludge the distribution of microorganism species was very similar in all experimental treatments (Poulsen, 2013b), except that in the unfertilized part was greater amount of free-living nitrogen-fixing bacteria (Cyanobacteria), and a higher content of the of bacteria which can survive high temperatures (Firmicutes) in the compost amended treatments. The prevalence of antibiotic-resistant bacteria (Pseudomonads) has been studied, and this work is currently being submitted. The main finding was that there measurable increases of resistant Pseudomonads relative to the unfertilized parcel until 3 weeks after application. After 9 weeks there was no difference and all treatments showed a very low incidence of antibiotic resistance. It is well known that soil is a very robust ecosystem, but it has been a pleasant surprise how resilient these soils have been. It would be appropriate in the near future to clarify the effect of the higher levels of the soil food web and possible unintended positive and negative effects on cultivated crops, but we have no reason to believe that there will be substantial effects.

As will be seen from the summary of recent assessments below, there is a large amount of data that allows an evaluation of the risk. While a complete risk assessment cannot be made, since there are some questions that still need attention, (i.e. emerging contaminants that need addressing), there is an overwhelming body of evidence indicating that recycling of sewage sludge on farmland is not constrained by concentrations of organic contaminants found in contemporary sewage sludges. Furthermore the consensus view therefore is that there appears to be no scientific rationale for including numerical limits on organic contaminants in quality assurance systems for the agricultural use of sewage sludge. Finally, the chemical quality of sludge in first world countries is continually improving and concentrations of potentially harmful and persistent organic compounds have declined to background values.

Recent reviews and risk assessments

Risk assessment of contaminants in sewage sludge applied on Norwegian soils

A comprehensive Norwegian study assessed the risk of using sewage sludge as fertilizer and soil conditioner in agriculture and using derived products public parks and private gardens (Eriksen, 2009). An assessment was made of the potential risk of dispersal of sewage sludge for soil living organisms, the aquatic environment, grazing animals, animals eating feed based on plants from sludge-treated soil, children eating soil, and humans consuming drinking water, crop plants and/or meat affected by the use of sludge as soil conditioner.

A risk assessment of all these exposure routes was made for the following contaminants:

Heavy metals: cadmium (Cd), phthalates (DEHP, DBP), lead (Pb), mercury (Hg), nickel (Ni), zink (Zn), copper (Cu) chromium (Cr)

Xenobiotic Organic Contaminants: octylphenols and octylphenol ethoxylates, nonylphenols and nonylphenol ethoxylates, linear alkylbenzenesulfonates (LAS), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs).

Furthermore the study evaluated the risk associated with a range of pharmaceuticals. The predicted environmental concentrations (PECs) in soil, as well as human and animal exposure to the contaminants following the use of sewage sludge as soil conditioner were estimated by use of mathematical modelling based on the guidelines given in the European Union's (EU) Technical Guidance Document on Risk Assessment (TGD). The risk assessment covered evaluation after one application and the potential accumulation of contaminants following repeated use of sewage sludge in a 100 year perspective.

The estimated predicted environmental concentration for each contaminant was compared with the available predicted no-effect concentration (PNEC) for soil. For heavy metals the model showed that no metal would reach the PNEC values within the timeframe of 100 years. Consequently it was considered that metals in sludge constituted a low risk to soil living organisms. However, the model estimates indicated that the soil concentrations of Cd, Hg, Cu and Zn, and partly also Pb would increase following repeated use of sewage sludge. Cadmium and Hg, as well as Pb are of particular concern due to their inherent toxic properties and an increase is undesirable even if the soil remain below the PNEC values.

Octylphenols, nonylphenols and LAS were the only contaminants where the PEC exceeded the PNEC. However, these are rapidly degradable substances ($t_{1/2}$ in soil = 8-10 days) where the highest concentrations were found immediately after application of sewage sludge followed by a rapid decrease. Taking into account the uncertainties related to the occurrence levels, and the rapid degradation in soil, it was considered that octylphenols, nonylphenols and LAS are of low concern. Only a few PAHs and PCBs were expected to accumulate with repeated use of sewage sludge over a 100 years period and the model indicated that the concentrations of these substances would be well below the PNEC value even at the end of the 100 year period.

All the assessed organic contaminants were found to constitute a low risk to the soil environment. Of the more than 1400 drug substances sold in Norway, only 14 were estimated to exceed cut-off values of 100 or 10 µg/kg soil after sludge application. For these substances no PNEC values in soil was available. Soil PNEC values for pharmaceuticals were therefore estimated from the aquatic PNEC values when available. The estimated soil concentrations of drug substances were low (concentration range 0.01 – 2 mg/kg dry weight (DW)) and well below the estimated PNEC values. Thus drug substances in sewage sludge was assessed to constitute a low risk for soil-living organisms.

The potential transfer to the aquatic environment of metals, organic contaminants and drug substances from sludge applied within the boundaries set by regulatory statutes was assessed to be of no significance.

The risk of adverse effects in farm animals grazing on or receiving feed from sewage sludge treated areas seems to be negligible for a range of contaminants. However, considering use of sewage sludge directly on grazing areas without ploughing lead might be an exception and may constitute a risk in young animals.

The human dietary intakes via the different exposure routes assessed were combined – i.e. drinking water, plant and animal derived food products. The estimated concentrations of contaminants in soil indicate that repeated application of sewage sludge on a field during a 100 year time period will lead to an increase in soil concentrations of certain heavy metals such as Cd and Hg. A consequence of this accumulation in soil may result in an undesirable increase in human dietary intake of particularly Cd, but also Hg. However, the increase in intake of metals from animal-derived food products or drinking water as a consequence of use of sewage sludge as fertilizer was estimated to be very low (<5% of estimated current total intake) and thus of low concern. The organic contaminants addressed in the Norwegian risk assessment are either degraded in the soil or poorly absorbed in plants. The assessment therefore indicated a low increase in human dietary exposure to organic contaminants from sewage treated soil it was opined that this additional exposure constitutes a low risk to the consumers.

It was deemed unlikely that antibacterial resistance may be promoted in the STP water, in the sludge or in the soil following application of sewage sludge as fertilizer. An exception might be a potential development of resistance to the fluoroquinolone ciprofloxacin in soil due to its persistence.

The risks were assessed chemical by chemical, since no methodology for the risk assessment of the mixture occurring in sewage sludge is available. Most of the estimated exposures were well below any predicted effect concentration, making any interaction less likely, unless the contaminants have the same mode of action.

A review of organic contaminants in sewage sludge (biosolids) and their significance for agricultural recycling

Smith (2009) reviewed the concentration data for organic contaminants (OCs) in sewage sludge and assessed the consequences and significance of OCs for the environment, human health and the food chain when sewage sludge is recycled to farmland as a fertilizer. He notes that according to the European Commission there are no recorded cases of human, animal or crop contamination due to the use of sludge on agricultural soils following the provisions of Directive 86/278/EEC. Despite the international support for recycling sludge to land, the acceptance of this practice among different European countries varies considerably and has declined markedly in some cases. For example, concerns about the potential consequences for human health and the environment of potentially toxic substances and harmful micro-organisms have led to the banning of the use of sludge in agriculture in Switzerland, despite official recognition that there is no conclusive scientific evidence that the practice is harmful in any way. Smith (2009) analyses available data on bulk-volume and industrial compounds, as well as endocrine disrupters, pharmaceuticals, antibiotics and personal-care products.

Human health risks

It is found that OCs present minimal risk to the human food chain from land application of sewage sludge. Based on the analytical evidence the most toxic compounds (e.g. TCDD) cannot be detected in sludge. These compounds are also influenced by a variety of mechanisms that prevent transfer to crop tissues and the human food chain, including: (i) rapid volatilization and loss to the atmosphere; (ii) rapid biodegradation and minimal or no persistence, or (iii) strong adsorption of persistent compounds.

The risk to human health via dietary intake of OCs from crops grown on sludge treated soils is minimal owing to the absence of crop uptake. In recent years the potential impacts on the food chain of persistent OCs in sludge, including PAHs, PCDD/Fs or PCBs, have been a key concern for agricultural utilization. However, international emission controls on the main point sources of these priority-persistent compounds have significantly reduced their entry into the environment and consequently also into the UWW collection system. Thus, atmospheric deposition and environmental cycling are the main sources of PCBs in sludge, and consequently the concentrations of this historically used chemical in sludge generally represent background environmental levels.

Antibiotic resistance

The possibility that sludge may contain populations of antibiotic-resistant bacteria and also trace concentrations of antibiotic compounds causing antibiotic has raised concerns.
Generally, antibiotic resistance is a transient characteristic and elevated resistance levels in soil are relatively quickly return to normal background values. This is because high maintenance requirements place the resistant organisms at a disadvantage; therefore, natural attenuation occurs when the selection pressure is removed. Application of sludge at normal agronomic rates, the relatively infrequent application of sludge to land and extended return periods are likely to permit natural attenuation of antibiotic-resistant bacteria populations in soil. However, a microbiological risk assessment should be completed to confirm that antibiotic-resistant microorganisms in sludge-treated soil represent a negligible risk to human health. This is the basis for designating the risk to human health from OCs as 'possible'.

Crop yields and soil fertility
Smith (2009) found no evidence that the vast majority of sludge-borne OCs have a detrimental impact on crop yield or soil microbial processes. Earlier concerns about the potential impact of LAS, a detergent surfactant present in large concentrations in sludge, on soil ecological processes have been further elucidated and shown to be unfounded. While the presence of large concentrations of certain high-volume bulk chemicals, such as LAS, warrants careful investigation and assessment of the risks to the environment when sludge is used as an agricultural soil amendment, this does not necessarily represent a hazard to the soil ecological environment. Phthalates were not found to cause any significant adverse effects on soil microbial processes or on soil fertility. In general, high-volume usage compounds have very low toxicity and degrade rapidly in soil. A number of emerging compounds were identified in this review as having a potential impact on soil microbes and these belong to the group of chemicals described as body-care products, e.g. triclosan, and the significance of these warrants further investigation.

Conclusive remarks
Despite the extensive range of organic chemicals that can be present in sewage sludge, the expanding experimental evidence base (147 papers in this review) indicates that these are not a significant limitation to the agricultural use of sewage sludge. This view is based on a technical evaluation of the situation, which acknowledges that the presence of effective source control measures and small concentrations of persistent contaminants in sludge, biodegradation and behaviour in soil, absence of crop uptake and sludge application practices minimize the potential impacts of OCs in sludge on soil quality, human health and the environment. The consensus view therefore is that there appears to be no scientific rationale for including numerical limits on OCs in quality assurance systems for the agricultural use of sewage sludge. Furthermore, the chemical quality of sludge is continually improving and concentrations of potentially harmful and persistent organic compounds have declined to background values. Thus, recycling sewage sludge on farmland is not constrained by concentrations of OCs found in contemporary sewage sludges. A number of issues, while unlikely to be significant for agricultural utilization, require further investigation and include: (i) the impacts of chlorinated paraffins on the food chain and human health, (ii) the risk assessment of the plasticizer di(2-ethylhexyl)phthalate, a bulk chemical present in large amounts in sludge, (iii) the microbiological risk assessment of antibioticresistant micro-organisms in sewage sludge and sludge-amended agricultural soil, and (iv) the potential

significance of personal-care products (e.g. triclosan), pharmaceuticals and endocrine-disrupting compounds in sludge on soil quality and human health.

Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids

The author of the aforementioned paper, later on published a review specifically on 'emerging' organic contaminants (Clarke and Smith, 2011). Of the 50 million chemicals entered in the Chemical Abstracts Registry approximately 143,000 chemicals are registered with the European Chemicals Agency for industrial use. Clarke and Smith (2011) identified research and monitoring priorities based on the following 5 criteria: **1.)** environmental persistence in soil environment (>6 months); **2.)** potential for human health impacts resulting from the land application of biosolids; **3.)** evidence or likelihood of bioaccumulation in humans or the environment; **4.)** evidence of ecotoxicity, and **5.)** the quality of empirical data and trends on the contaminant in biosolids internationally.

They found that two chemical classes warrant particular note. These are the perflourinated chemicals (PFCs) and polychlorinated alkanes (PCAs). PFCs are an emerging environmental concern as they have been detected in human blood and environmental samples throughout the world. They have a unique chemistry for a chemical defined as a POP that facilitates a degree of water solubility, and therefore, there is an increased likelihood of exposure through all pathways (water contamination, plant accumulation and grazing animal accumulation) compared to other POPs. PCAs were found at relatively high concentrations in sludge (mean concentration 1800 mg kg^{-1} dw). Comparison of the concentrations of these compounds to PCBs and PCDD/Fs shows that the PCA content in sludge is three orders of magnitude higher than PCB values for instance, and signals the importance of further investigations into the significance of PCAs in biosolids for land application. While recycling biosolids on land is recognised internationally as the most sustainable option for managing the residual sludge from urban wastewater treatment, continued vigilance in assessing the significance and implications of 'emerging' OCs in sludge is necessary to support and ensure the long-term sustainability of this management option.

Jensen J., Magid J., Ingvertsen S.T. 2012. Risk evaluation of five groups of persistent organic contaminants in sewage sludge. Danish EPA

The aim was to elucidate the possible risks from emerging compounds to soil organisms. The studied compounds include brominated flame retardants, pharmaceuticals, musks, polyflourinated substances and PCBs. Using the recommended REACH model specified in the EU program for risk assessment of new and existing industrial chemicals expected long-term concentrations in agricultural soils were calculated on the basis of relative worse-case input. Depending on the data material the risk assessment procedure in REACH requires a minimum margin of a factor 10-1000 between the expected concentration in the soil and the concentration at which there is no evidence of negative effects. All groups of substances have been found in Danish sludge, but typically in concentrations that are below most European and American measurements. Four of these: PCBs, pharmaceuticals, musks and brominated flame retardants are most likely not an environmental problem for soil organisms, crops and other plants in relation to sewage sludge. Assuming long-term use of sludge with the highest Danish measured concentrations of polyflourinated substances safety margins are bordering the EU recommendations in its guidelines under the REACH program. It would therefore be appropriate to examine these substances actual effect further in long-term studies, in order to reduce the uncertainty that exists about its influence.

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