Using *Salix* as a bio-filter for Cadmium

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Abstract

Sewage sludge often contains cadmium (Cd), a metal which is highly toxic for humans. When applied to a field of *Salix*, Cd can be taken up through the roots and stored in the tree's biomass. A numerical solute transport model was created to simulate this uptake process and three major issues were addressed: is the current maximum allowed loading of Cd on a field reasonable? How much Cd can be applied to *Salix* plantations during a limited time for a secure future food production? How much Cd can be applied to a field before leaching causes a serious pollution of groundwater?

The results suggest that the current limit of Cd loading can be increased. When application time is set to 100 or 20 years, wheat production is possible again 150 and 50 years respectively, after the start of the simulation. Regarding the suggested WHO limit of Cd concentration in groundwater, 21 mg Cd m^{-2} can be applied annually without exceeding this limit. Nevertheless, this model is simplified and many factors are not taken into account, which makes it unsuitable as a base for important decisions about remediation. With more research on the effects of the various parameters and a more complex model, realistic values could be approached closer.

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1 Introduction

Food production requires large amounts of fertilizers to supply the world's population with nutrition. While synthetic fertilizers are being assembled in factories, readily available resources can be used instead to lower the environmental impact. Sewage sludge, a by-product from wastewater treatment plants, can be used as a fertilizer on agricultural fields in order to increase its nutrient content and improve the amount of soil organic matter in the soil (Bergkvist et al. 2003). However, sewage sludge also contains less desirable trace elements. One of the more toxic metals that are found in sewage sludge is cadmium, Cd. It is especially problematic because it is highly mobile in soil water and is bioavailable, thus it can be taken up by food-crops that are grown in Cd-contaminated fields (Bergkvist et al. 2003). Food that becomes contaminated with high concentrations of Cd can pose a serious health risk to humans. A prominent reason for this is that Cd is stored for a long time in our kidneys, where it can cause severe damage, if consumed in larger amounts over a long time period (Livsmedelsverket, 2021). Consumption of Cd is also related to an increased risk of bone fractures, as well as the risk of developing cancer (Livsmedelsverket, 2021).

Cd is regularly deposited onto farmland in small concentrations. A diffuse input due to deposition of atmospheric Cd derived from mining and coal industries (Bergkvist et al. 2003) provides an uncontrolled source. Moreover, Cd can also be applied to the fields through manure, contaminated phosphorus fertilizers and lime (Bergkvist et al., 2003). If sewage sludge is applied to a field, then it is usually the primary source of Cd in the soil.

Phytoextraction has proved a very promising technique for in situ remediation of Cd-contaminated soil (Klang-Westin & Eriksson 2003). Bio-filter, consisting of non-food plants with a high ability to take up the contaminant, are planted in order to extract the contaminant from soil solute and store it in biomass. The accumulated Cd in the plant is later removed from the site through harvest. Different plant species can be more or less suited for remediation of polluted soil. There are examples of plants, so-called "hyper-accumulators", which can accumulate very large quantities of Cd, $\geq$ 0.01% Cd in leaf dry mass (Klang-Westin & Eriksson 2003). Multiple studies have shown that *Salix* stands show a great potential in removing Cd from contaminated soils and could thus be used for phytoremediation purposes (Klang-Westin & Eriksson 2003; Eriksson & Ledin 1999; Greger & Landberg 1999).

Compared to the "hyper-accumulator-species", *Salix'*s rate of Cd-uptake is not as efficient and it would rather be categorized as a high-accumulator. However, many other aspects of *Salix* add to its potential for soil remediation. First of all, *Salix* has a very rapid biomass production. According to Kubátová et al (2016), phytoextraction efficiency is strongly dependent on yield of biomass as well as the concentration of the contaminant in said biomass. In an experiment conducted on Czech soil, one type of *Salix* clone produced up to 15 ton dry material ha^{-1} year^{-1}. This same type of clone had a high accumulation of Cd in twigs (41.9 mg kg^{-1}) and leaves (76.8 mg kg^{-1}). Fischerová *et al.* (2006, see Kubátová et al,

2016) found that some *Salix* could remove up to 15 to 20 % of Cd in soil over a period of four years. Secondly, *Salix* can be grown on soils where other species have difficulty to establish or reestablish (e.g. wet, saline or oligotrophic conditions) (Kuzovkina and Quigley, 2005). Finally, the harvested yield of *Salix* stands can be used as climate neutral biofuel, in which the Cd could be safely collected after combustion (Klang-Westin & Eriksson 2003). In addition, *Salix* can also provide an important habitat for insects, nesting birds and fish (if placed by the water (Kuzovkina and Quigley, 2005)).

Following the precautionary principle, the current limit of Cd loading onto arable land in Sweden has been set to 0.075 mg m^{-2} $year^{-1}$, which is rather strict compared to other countries' limits. The limit applies to all plant species regardless of Cd uptake ability, in order to prevent the risk of Cd accumulation in the field. As *Salix* has a high ability to take up the contaminant, it might be possible to apply larger Cd concentrations on *Salix* fields. Yet, a new suggested limit should not solely be based upon uptake capacity, but also have land use flexibility in mind. *Salix* will rarely be of permanent presence in the field, and the limit of Cd loading should ensure the possibility of safe food production within a realistic time period. In Sweden, the most common food crop is winter wheat (World Grain, 2013) and research has suggested a limit of 1.9 mg Cd m^{-3} in topsoil layers for wheat production to avoid risking the health of the population (Jarvis et al., 2020). Another relevant limit is set by the World Health Organization (WHO) to protect groundwater from contamination, in which it is stated that the leachate to groundwater should not exceed concentrations of 3 mg Cd m^{-3} (Jarvis et al., 2020). These two limits (maximum Cd concentration in food production and groundwater contamination) can act as guides in the search for a more suitable limit for Cd loading onto *Salix* fields.

Because the soil system is dependent on so many interacting parameters, a model can be very useful in order to improve the understanding of how Cd moves after application and thereby the long-term effects of using sewage sludge. This can be important for processes of planning and decision making, such as determining an appropriate maximum allowed loading of Cd on soil where *Salix* is grown.

1.1 Aim

The principal objective of this project is to investigate the possible use of willows (*Salix Sp.*) as a means of phytoremediation in Cd contaminated soils. Cd transport in soil and its uptake by plants is modelled. Outputs of this report address the following questions:

i) Is the current maximum yearly loading of Cd in Sweden (0.075 mg m^{-2} $year^{-1}$) reasonable on a site where *Salix* is being grown? Could it be increased or should it be reduced?

ii) What Cd loading range ensures fulfillment of the limit concentration in the groundwater leachate set by WHO (3 mg Cd m^{-3})? i.e. What are the risks of excessive Cd leaching to groundwater?

iii) When 1 mg m^{-2} $year^{-1}$ of Cd is applied, how much time do the plants need to remediate the contaminated soil to the extent that it will be suitable for food production again?

iiii) How much Cd (mg m^{-2} $year^{-1}$) can be applied onto *Salix* during a limited time period to ensure safe food production within a foreseeable future?

2 Material and Method

2.1 Model description

For modelling the cadmium uptake by willows, a numerical solute transport model based on the convection-dispersion equation was created by using the program Stella Professional Version 2.1.3.

As the process of phytoremediation is relatively slow, time periods between 300 up to 3000 years were chosen, depending on how long the sludge was applied to capture the full process. With a time span that long, the water flow rate can be approximated as a steady state and calculated from constant values of precipitation and evapotranspiration. Due to this simplification, the water content (theta) figures in the model as an input parameter with a constant value, which is representative for an average soil type and over the course of the year (see table 1). The values used for precipitation vary between 500 and 1300 mm/year, which is common for the Swedish environment. Additionally, all effects of seasons on phytoremediation were ignored for this model.

The Advection-dispersion equation, where advection = convection, was used in order to calculate the movement of dissolved Cd in the water.

$$\frac{\partial A}{\partial t} = \frac{\partial}{\partial z}\left\{\theta D\left(\frac{\partial c}{\partial z}\right) - qc\right\}$$

Important parameters that are needed to calculate the advection-dispersion equation is the adsorption coefficient Kd, which determines the relationship between how much solute is bound to solids or dissolved in solution, i.e C in the model. And D, which can be considered a diffusion dispersivity coefficient which affects the spreading of the solute pulse that moves through the soil. In this model, values for dispersivity and Kd are average constant values based on data from experiments where *Salix* is grown under Swedish conditions (see table 1)

(Jarvis et al., 2020). The same applies to the other parameters that are defining the soil properties in this model, such as bulk density and water content, where the chosen values are also typical for sites with *Salix* in Sweden (see table 1).

Table 1: parameters defining soil properties and their default values based on experimental data from *Salix* grown in Swedish conditions (Jarvis et al., 2020).

Parameter	bulk density	water content	dispersivity	Kd
Default values	1400 kg/m^3	0.3 cm^3/cm^3	0.03 cm	0.15 cm^3/g

The upper boundary condition in the model is set as the application rate of Cd, based on the concentration of cadmium in the sludge combined with the amount and time of sludge input, as well as the input from deposition and contaminated fertilizers. Whereas the lower boundary condition is the convective transport of the dissolved Cd. The dispersion in the bottom soil layer is set to zero.

Furthemore, the Cd uptake with water by *Salix* over the roots is defined by the parameters describing the amount of cadmium in the soil as well as the parameters 'harvest' [kg m^{-2} $year^{-1}$] (biomass containing cadmium and being removed from the study site) and an 'uptake coefficient' [m^3 kg^{-1}]. The resulting equation is:

Uptake [mg m^{-2} $year^{-1}$] =
uptake coefficient [m^3 kg^{-1}] * concentration of dissolved Cd [mg m^{-3}] *
harvest [kg m^{-2} $year^{-1}$] * (layer thickness [m] / profile depth [m])

Definitions of root depth and the root density are not included in the model, but it is assumed that the roots are spread evenly throughout every layer down until the water table.

2.2 Modeled scenarios

The application of Cd through sewage sludge will hereafter be referred to as the application of Cd. Besides the sewage sludge, the total Cd input into the soil in the model also includes atmospheric deposition and contaminated fertilizers. These are kept at a constant value (0.1 mg Cd m^{-2} $year^{-1}$) and are not included in the numeric values presented as application of Cd. In the following four scenarios, precipitation is set to 700 mm $year^{-1}$, and the initial values of Cd in the soil layers are 0.24 mg m^{-3} (0 to 0.25 m depth) and 0.16 mg m^{-3} (0.25 to 1 m depth).

Scenario 1: Current limit for Cd application

To investigate whether the current Cd loading limit of 0.075 mg m^{-2} $year^{-1}$ is reasonable on *Salix* plantations (i.e. the Cd concentration in the topsoil and in the leachate stays below the limits of 1.9 mg m^{-3} and 3 mg m^{-3}, respectively) , the parameter Cd loading was simply set to this value and the model was run.

Scenario 2: Groundwater leaching

A simulation was run to determine the maximum possible Cd loading onto soil without the groundwater leachate exceeding WHO:s limit of 3 mg Cd m^{-3}. In this scenario, sewage sludge was applied for 100 years and the *Salix* uptake was constant for 3000 years. The application concentration was increased until Cd concentration at 1 m depth almost reached the WHO limit.

Scenario 3: Recovery time with default values

The model used in this report had initial values of Cd concentration and years of application of 1 mg m^{-3} and 100 years respectively. A simulation was run using these values as a sort of pretest to see how long it would take for the soil to recover and if there was a risk of leaching into groundwater. The following two scenarios were derived from this.

Scenario 4: Future food production

It can be a reasonable assumption that a landowner will not grow energy forests of *Salix* for an indefinite future. By the time of crop change to food production, the concentration of Cd in the soil needs to be at safe levels for human health, which for winter wheat is 1.9 mg Cd m^{-3}. Thus, an investigation is needed to estimate the maximum amount of Cd application onto soil under a certain period of time, plus a period where no sludge is applied so the *Salix* can extract the redundant Cd, resulting in concentrations below the permitted level.

A time limit of 50 years from initial sewage sludge application was set for the soil to recover, as this can be considered a realistic period after which the farmer might want to repurpose the land. Sewage sludge was applied for the first 20 years, and the following 30 years the application was removed to let the *Salix* take up the accumulated cadmium in the soil.

The uptake parameter of the plant in Stella was changed to contain a function simulating the replacement of *Salix* after 50 years with winter wheat. For this, two parameters for the plant uptake was adjusted; the uptake coefficient of Cd (1/10 of that of *Salix* (Jarvis et al., 2020)) and harvest (0.65 kg m^{-2} $year^{-1}$ compared to 0.8 kg m^{-2} $year^{-1}$ for *Salix* (SCB, 2021)). This was done in order to investigate if the concentrations of Cd would remain under the limit even without phytoremediation.

To identify the maximum Cd input that could be applied without exceeding the limit of 1.9 mg Cd m^{-3} in topsoil layers after 50 years, the value of sludge application was changed until the Cd concentration after 50 years was just below the limit of 1.9 mg Cd m^{-3}.

Table 2: Modeled scenarios with altering Cd concentration application and years of application

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Application [mg Cd m^{-2} $year^{-1}$]	0.075	21	1	1.4
Years applied	100	100	100	20
Sought limit [mg Cd m^{-3}]		Bottom layer 3.0	Topsoil 1.9	Topsoil 1.9

2.2 Sensitivity analysis

To find out which parameters have had the most significant influence, a sensitivity analysis was performed on the following: Slope of the sorption isotherm for cadmium (Kd), Water content (theta), Cd loading into soil, and the Precipitation. The model was run for different values for one parameter at a time in respectively chosen ranges and graphs were created to display the influence of each parameter for the Cd concentration in the topsoil layer after 150 years.

3 Results

3.1 Modeled scenarios

Scenario 1: Current limit for Cd application

The result of the simulation for the current limit (0.075 mg Cd m^{-2} $year^{-1}$, 100 years application) shows that Cd concentration in top-soil solution never exceeds the suggested limit of 1.9 mg m^{-3} considered safe for wheat production (figure 1). Furthermore, the graph shows that the concentration of Cd in top soil solution never increases, showing that the uptake capacity of *Salix* is greater than the current allowed limit. At 1 m depth, the concentration of Cd only reaches one third of the maximum permissible value at the beginning and is then decreasing steadily throughout the simulation, thus indicating that leachate in groundwater will not exceed the WHO limit of 3 mg m^{-3} $year^{-1}$.

After approximately 1500 years, the system reaches a steady state and both Cd concentrations stabilize at a level well below the suggested limits (0.44 and 0.08, in topsoil and 1 m depth respectively).

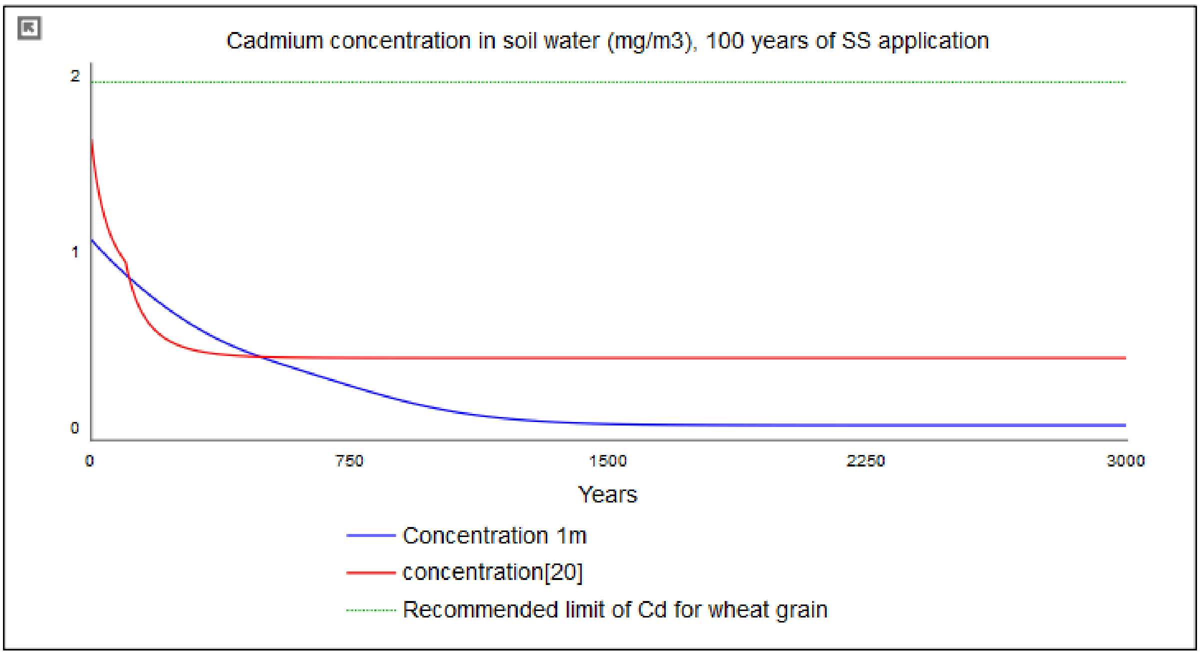

Figure 1: concentration of Cd in topsoil solution and at 1 m depth, applying the maximum allowed Cd amount 0.075 mg Cd $m^{-2}year^{-1}$ for 100 years. SS = sewage sludge. The red line illustrates Cd concentrations in topsoil solute, and the blue line illustrates the Cd concentration at 1 m depth, representing groundwater leachate.

Scenario 2: Groundwater leaching

In this scenario (21 mg Cd m^{-2} $year^{-1}$, 100 years application), a maximum concentration of 2.98 mg Cd m^{-3} is reached in the bottom layer (1 m depth) after approximately 840 years, see figure 2. Hence, in this model, this is the highest allowable amount of Cd that can be applied to the soil in order to remain at concentrations lower than the WHO limit of 3 mg Cd m^{-3} leaching into the groundwater. In the topsoil however, the concentration peaks at 74 mg Cd m^{-3}, and it would take about 385 years from the first year of application before the soil Cd concentration passes below 1.9 mg m^{-3} and would be safe for wheat production again.

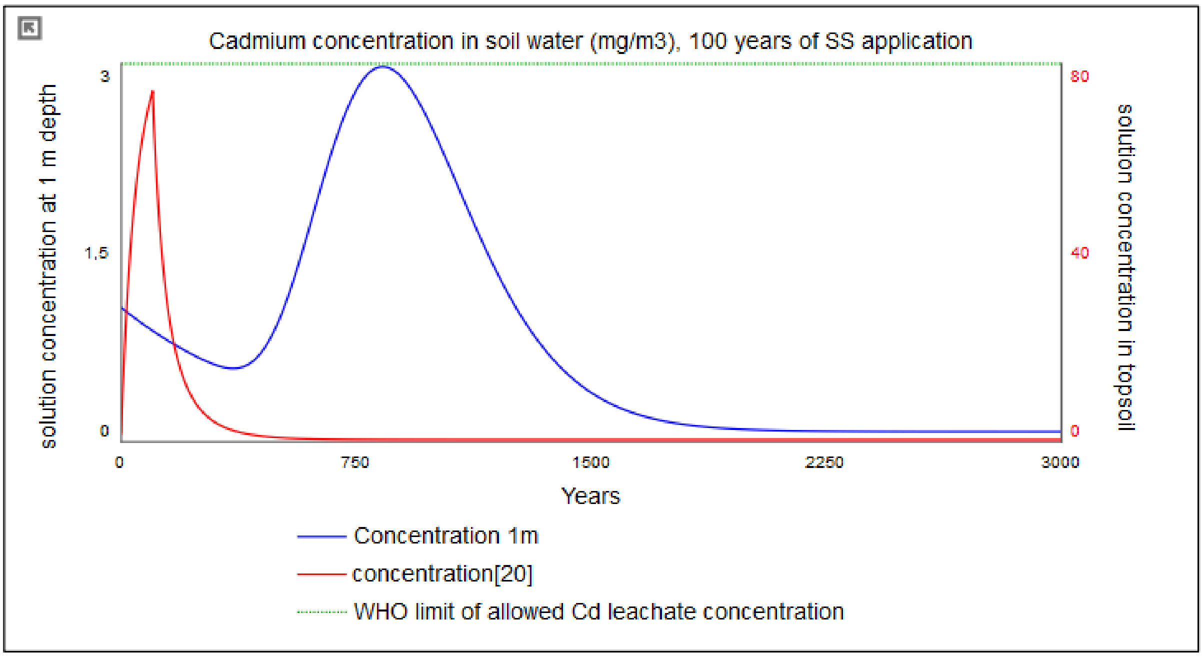

Figure 2: concentration of Cd in topsoil solution and at 1 m depth, applying 21 mg Cd m^{-2} $year^{-1}$ for 100 years. SS = sewage sludge. Note that there are two y-axes, and that the WHO limit is on the left axis. The red line illustrates Cd concentrations in topsoil solute, and the blue line illustrates the Cd concentration at 1 m depth, representing groundwater leachate.

Scenario 3: Recovery time with default values

Figure 3 shows the scenario for food production (1 mg Cd m^{-2} $year^{-1}$, 100 years application). The Cd concentration in the topsoil layer dropped under the recommended limit for safe wheat production after 150 years, counting from the start of the simulation. The graph shows the first 300 years of the simulation, when the concentration slowly increases, reaches over 4 mg Cd m^{-2} $year^{-1}$ and then rapidly drops.

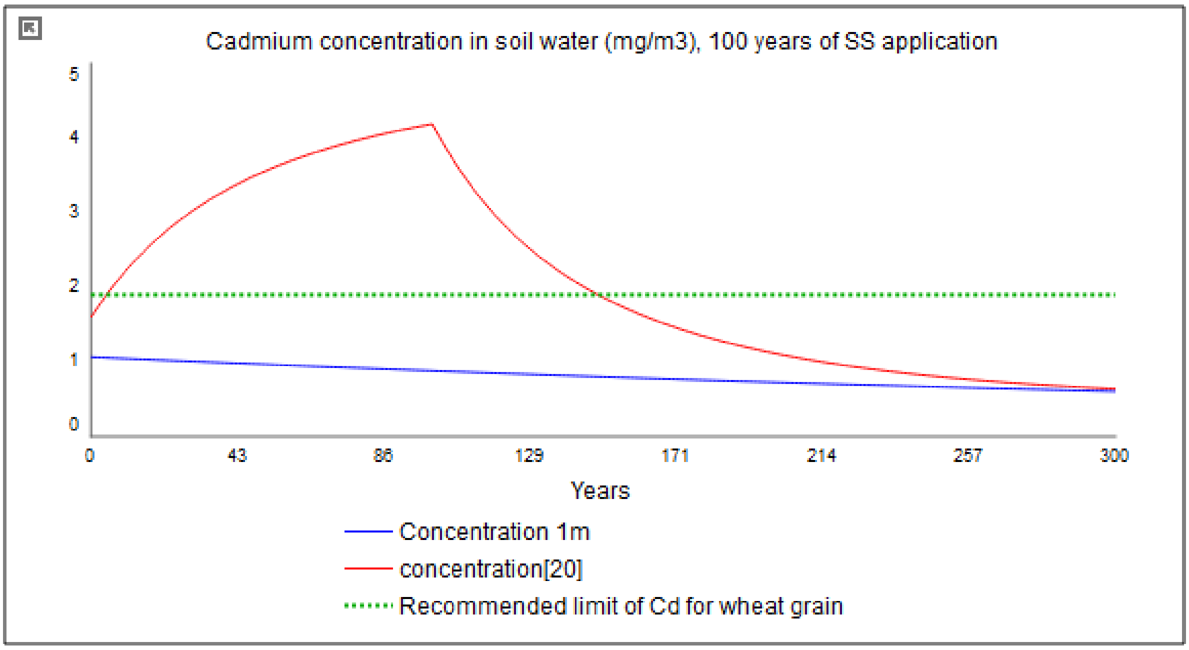

Figure 3: concentration of Cd in topsoil solution and at 1 m depth, applying 1 mg Cd m^{-2} $year^{-1}$ for 100 years. SS = sewage sludge. The red line illustrates Cd concentrations in topsoil solute, and the blue line illustrates the Cd concentration at 1 m depth, representing groundwater leachate.

Scenario 4: Future food production

Figure 4 illustrates a scenario where *Salix* is removed after 50 years (1.4 mg m^{-2} Cd $year^{-1}$, 20 years application) and replaced by winter wheat. The concentration in the topsoil layer first exceeds the suggested limit of 1.9 mg m^{-3} with a peak of 3.25 mg m^{-3} after 20 years, and passes below the limit (1.88 mg m^{-3}) 50 years after the first application.

Salix was removed from the system after the soil had been remediated (1.88 mg m^{-3}), yet the model shows no further increase in Cd concentrations accumulated from atmospheric deposition and contaminated fertilizers. Uptake of winter wheat and leaching of Cd into deeper soil keeps the concentration low.

A peak in the concentration at 1 m depth of 1.07 mg m^{-3} $year^{-1}$ after 725 years shows that the available Cd in the soil has translocated towards the lower layers in the profile. It never reaches WHO:s limit of 3 mg m^{-3}. After about 2000 years the Cd concentration remains stable at 0.49 and 0.42 mg m^{-3} in the topsoil and at 1 m depth respectively.

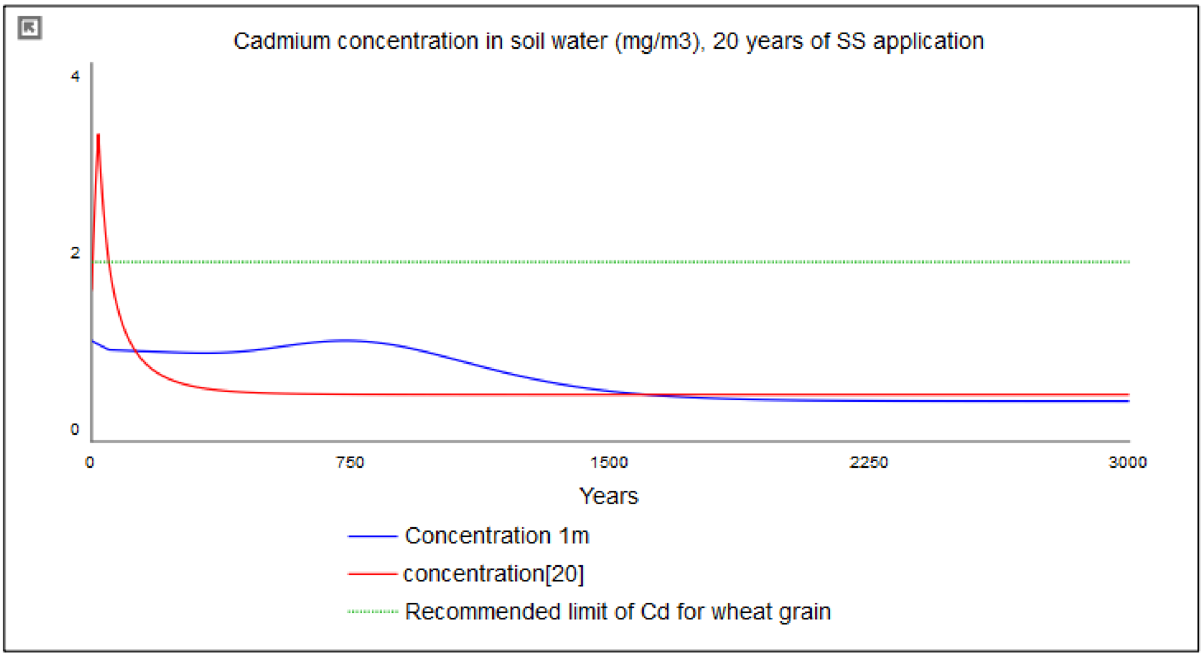

Figure 4: concentration of Cd in topsoil solution and at 1 m depth, applying 1.4 mg Cd m^{-2} $year^{-1}$ for 20 years. *Salix* is replaced by winter wheat after 50 years. SS = sewage sludge. The red line illustrates Cd concentrations in topsoil solute, and the blue line illustrates the Cd concentration at 1 m depth, representing groundwater leachate.

3.2 Sensitivity analysis

Results from the sensitivity analysis of Kd and theta are omitted in this report, as their influence on the topsoil Cd concentration was found to be only marginal.

Parameter Sludge

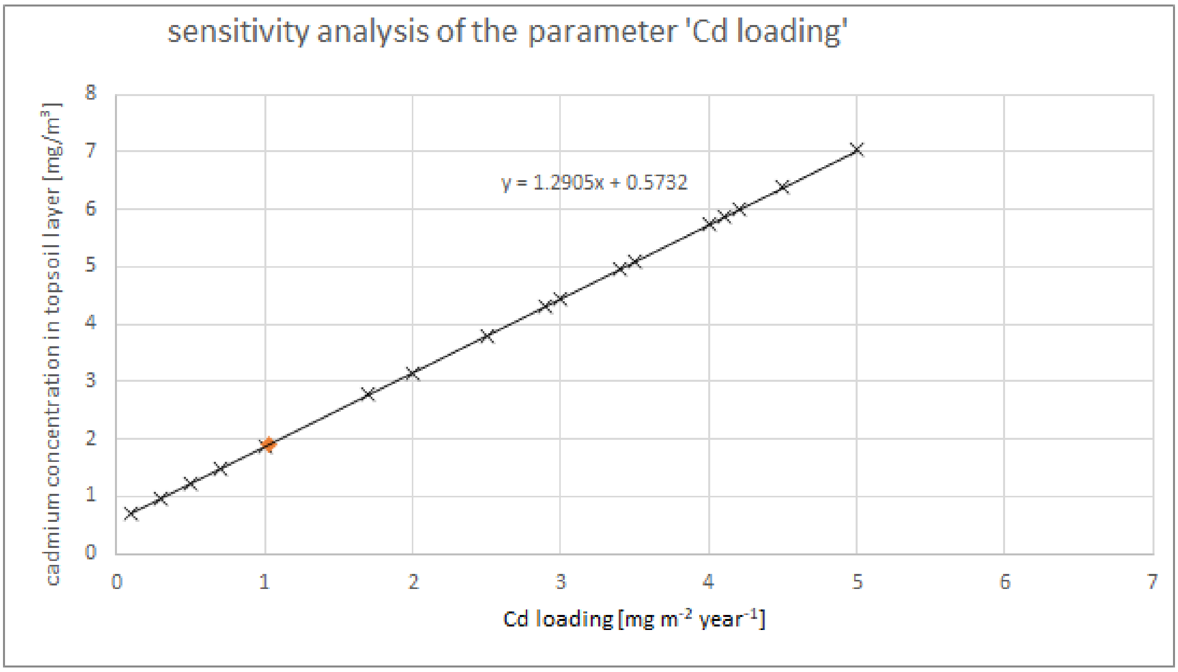

Figure 5: the concentration in the topsoil layer at 150 years for various values of the parameter Cd loading if the application time is 100 years. The point where the concentration is 1.9 mg/m³ is marked orange.

The relation between the Cd loading and Cd concentration in the topsoil layer is linear with an acclivity of 1.2905. Hence, by increasing Cd loading, the concentration will increase slightly more, so the model is clearly sensitive to this parameter.

To see for which amount of Cd loading in the sludge the cadmium concentration in the topsoil layer exceeds the limit for growing wheat can be calculated now as follows:

$$\text{Cd loading} = (1.9 - 0.5732) / 1.2905$$
$$= 1.0281 \ [\text{mg m}^{-2} \text{year}^{-1}]$$

The values for the parameter Cd loading were chosen between zero and five for a realistic approach. Within this chosen range, the concentration of cadmium never exceeds the limit of 1.9 mg/m³, which is required to use the field for wheat production.

Parameter Precipitation

As seen in Figure 6, the concentration of Cd solute in topsoil changes significantly within the chosen range of Precipitation. The relation between the two variables is non-linear. The equation representing this relation is approximately quadratic.

Using the Precipitation's lower extreme value of 0,55 m per year, the Cd concentration rises up to 6,2 mg m^{-3}. The subsequent remediation of the soil is very slow, taking 500 years before the soil is suitable for wheat production again. In contrast, the Precipitation's upper extreme value of 1,3 m per year causes the Cd concentration never to exceed 1,9 mg m^{-3}, i.e the safe wheat production limit. While leaching is indeed higher than in the first scenario (due to the much higher pore water velocity), it still stays way below the WHO limit for Cd concentration in groundwater leachate.

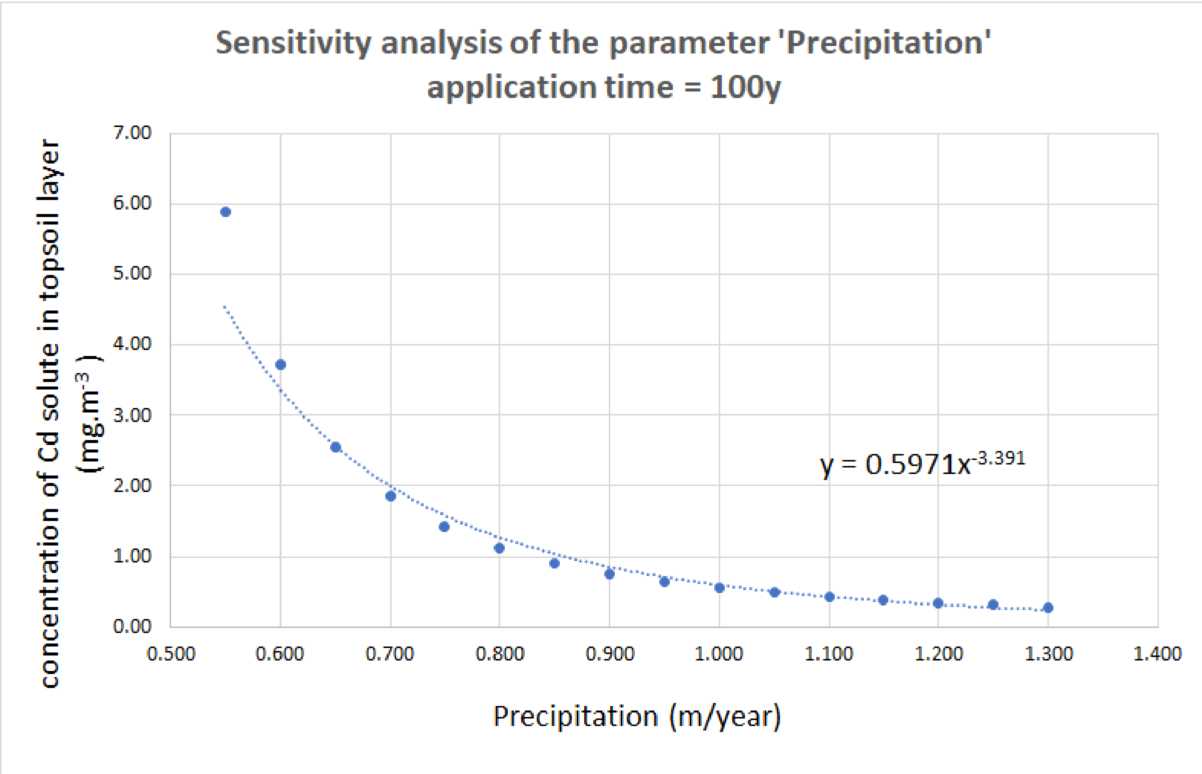

Figure 6: Sensitivity analysis for Precipitation ranging between 0,55 - 1,3 m $year^{-1}$ with a step of 0,05. Cd loading was set to 1 mg m^{-2} $year^{-1}$ for 100 years. The Cd concentration values were measured after 150 years from the start of the simulation

4 Discussion

Modeled scenarios

The model suggests that the current limit of Cd loading (0.075 mg m^{-2} $year^{-1}$) onto soil where *Salix* is grown, can be increased. In the first scenario, where 0.075 mg Cd m^{-2} is applied for 100 years, the highest concentration of Cd in solute in the topsoil is 1.6 mg m^{-3}, which is below the suggested limit for safe wheat production of 1.9 mg m^{-3} Cd. As presented in figure 1, the Cd concentration never increases as *Salix*'s uptake rate is larger than the application rate. At 1 m depth, the maximum Cd concentration in this scenario is 1.07 mg m^{-3}, so the WHO:s limit of 3 mg Cd m^{-3} is by far avoided. This indicates that there is room for an increase in maximum allowed Cd concentration on soil where *Salix* is grown.

To avoid leaching of Cd into groundwater (scenario 2) in higher concentrations than WHO's limit of 3 mg Cd m^{-3}, up to 21 mg Cd m^{-2} can be applied annually to *Salix* plantations over a period of 100 years (precipitation of 700 mm $year^{-1}$) according to the results. This is 280 times higher than the current allowed limit of Cd load. Yet, this is not recommended as the land would recover after 385 years to be suitable for safe food production. This can be argued to be a too large time scale to justify such high concentrations of Cd for 100 years.

In scenario 4 (food production), a value of Cd concentration was sought based on a time limit set for the soil to recover enough for safe food production. This might be considered a more realistic approach to produce a new suggestion for a loading limit. Results showed that as long as the concentration in the topsoil is kept at a safe level for food production, there is no risk of exceeding WHO:s limit for Cd leaching into groundwater. When considering a change in the maximum allowance of Cd concentration onto *Salix* plantations, it is wise to base the new limit upon the prospect of future food production, and not upon the risk of groundwater contamination. The model shows that as long as Cd concentrations are safe for consumption, there is no risk of unsafe groundwater leachate. This conclusion is not surprising as the upper allowable limit (topsoil 1.9 mg Cd m^{-3}) is lower than the lower allowable limit (1 m depth 3 mg Cd m^{-3}). As root uptake and diffusion occurs with time, the amount of Cd reaching the bottom layer is logically lower than at the top.

While the definite numbers found in this analysis is highly unreliable due to the models inability to mirror the complexity of reality, it still indicates that the allowable Cd concentration in loadings onto *Salix* can be increased and that the new limit should be largely based on safe human consumption of crops rather than on dangers of groundwater contamination.

However, as this model is highly simplified and approaches, but does not reach realistic outputs precisely enough, it is not recommended to increase the Cd loading based on the presented results alone.

Sensitivity analysis

From the four chosen parameters (Kd, theta, Cd loading, precipitation) for the sensitivity analysis, only two were found to have a remarkable influence on the model (Cd loading, precipitation). When changing the value of precipitation, the ETA was left unaltered. This is an unrealistic scenario, as these two parameters are usually correlated. The ETA tends to increase together with the precipitation until reaching the value that is optimal for the respective plant (De Niel et al., 2019). Thus, with lower precipitation values (<700 mm $year^{-1}$), ETA should be changed accordingly in order to avoid biased pore water velocity values.

Limits and weaknesses of the model

The possible weaknesses of the model and the whole project are - as aforementioned - the exclusion of important factors or scenarios and their influence on the Cd concentration in the topsoil layer as well as in the groundwater. A long period of drought for example could cause sludge and rainwater runoff, resulting in the Cd not being soaked up in the soil. Environmental conditions such as pH values of the soil and the rain, but also the characteristics of different soil types can affect the Cd uptake. Moreover, foliage accumulation on the topsoil layer in autumn causes Cd to agglomerate and change its concentration in the upper soil layer considerably. Also the root depth and the root distribution were simplified rather than realistically represented. Moreover, possible fluctuations in the harvest are not considered, such as a significantly smaller biomass production at the beginning of the plantation growth. Another important factor that was ignored is the winter period, which is considerably long in Sweden. During this time, neither water nor Cadmium uptake occurs, which would presumably change the results significantly. More research on all the factors and their impact on Cadmium uptake by *Salix*, as well as their influence on each other could be useful to gain a deeper understanding of the modelled process. By furthermore including all those effects in the model, more realistic results could be achieved.

5 Conclusions

The results of this model indicate that the current maximum allowed Cadmium loading (0.075 mg Cd m^{-2} $year^{-1}$) can be increased, as the uptake by *Salix* highly exceeds the concentration increase induced by loading. However, it is important to state that the model is highly simplified and many factors are not taken into account and therefore, it should not be used as the sole base for important decisions.

Considering only the leaching aspect, up to 21 mg Cd m^{-2} $year^{-1}$ could be applied without exceeding the WHO limit. Nevertheless, this would leave the site unsuitable for food production over multiple hundred years and hence, the range of cadmium loading should be determined preferably with emphasis on the topsoil concentration, in case future agricultural use of the site is intended.

When applying 1 mg Cd m^{-2} $year^{-1}$ for 100 years, the soil was suitable for safe wheat production again about 150 years after the start of the simulation. When changing the application time to 20 years, the application could be increased to 1,4 mg Cd m^{-2} $year^{-1}$, while the remediation time was shortened to 50 years after the simulation started.

As the model is highly simplified, many factors are ignored in this simulation, which could change the results remarkably. The biggest factor not included are possibly the seasons, which for example influence other parameters such as precipitation or evapotranspiration and during winter, Cd uptake does not even occur at all. To achieve a more realistic approach, research on all impacts and their effect on Cd uptake is needed, as well as then including all known factors into the model without further simplification.

References

Bergkvist, P. & Jarvis, N. (2004). Modeling Organic Carbon Dynamics and Cadmium Fate in Long-Term Sludge-Amended Soil. *Journal of Environmental Quality*, 33 (1), 181–191. https://doi.org/10.2134/jeq2004.1810

Bergkvist, P., Jarvis, N., Berggren, D. & Carlgren, K. (2003). Long-term effects of sewage sludge applications on soil properties, cadmium availability and distribution in arable soil. *Agriculture, Ecosystems & Environment*, 97 (1), 167–179. https://doi.org/10.1016/S0167-8809(03)00121-X

De Niel, J., Van Uytven, E. & Willems, P. (2019). On the correlation between precipitation and potential evapotranspiration climate change signals for hydrological impact analyses. *Hydrological Sciences Journal*, 64:4, 420-433, DOI: 10.1080/02626667.2019.1587615

Eriksson, J. & Ledin, S. (1999). Changes in phytoavailability and concentration of cadmium in soil following long term Salix cropping. *Water, air, and soil pollution*,. https://link.springer.com/article/10.1023/A:1005050005459 [2021-10-08]

Greger, M. & Landberg, T. (1999). Use of willow in phytoextraction. *Int J Phytorem* 1: 115–123. https://doi.org/10.1080/15226519908500010)

Jarvis, N., Lewann, E., Larsbo, M., Eckersten, H., Moeys, J., Sandin, M., Koestel, J. & Coucheney, E. (2020). Course compendium - Soil Water Processes in Agro-Ecosystems. *Swedish University of Agricultural Sciences*

Klang-Westin, E. & Eriksson, J. (2003). Potential of Salix as phytoextractor for Cd on moderately contaminated soils. *Plant and Soil*, 249 (1), 127–137. https://doi.org/10.1023/A:1022585404481

Kuzovkina, Y.A. and Quigley, M.F., (2005). Willows beyond wetlands: uses of Salix L. species for environmental projects. *Water, Air, and Soil Pollution*, 162(1), pp.183-204.

Kubátová, P., Hejcman, M., Száková, J., Vondráčková, S. and Tlustoš, P., (2016). Effects of sewage sludge application on biomass production and concentrations of Cd, Pb and Zn in shoots of Salix and Populus clones: Improvement of phytoremediation efficiency in contaminated soils. *BioEnergy Research*, 9(3), pp.809-819

Livsmedelsverket (2021). *Kadmium*. https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/metaller1/kadmium?AspxAutoDetectCookieSupport=1 [2021-10-08]

Statistiska centralbyrån (2021) Winter wheat, spring wheat and rye, yield per hectare (scb.se) [2021-10-18]

World Grain (2013). *Focus on Sweden*. Focus on Sweden | World-grain.com | December 09, 2013 14:26 [2021-10-18]