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Modeling cadmium in the feed chain and cattle organs

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The objectives of this study were to estimate cadmium contamination levels in different scenarios related to soil characteristics and assumptions regarding cadmium accumulation in the animal tissues, using quantitative supply chain modeling. The model takes into account soil cadmium levels, soil pH, soil-to-plant transfer, animal consumption patterns, and transfer into animal organs (liver and kidneys). The model was applied to cattle up to the age of six years which were fed roughage (maize and grass) and compound feed. Cadmium content in roughage and cadmium intake by cattle were calculated for six different (soil) scenarios varying in soil cadmium levels and soil pH. For each of the six scenarios, the carry-over of cadmium from intake into the cattle organs was estimated applying two model assumptions, *i.e.*, linear accumulation and a steady state situation. The results showed that only in the most extreme soil scenario (cadmium level 2.5 $mg \cdot kg^{-1}$, pH 4.5), cadmium exceeded the EC maximum tolerated level in roughage. Assuming linear accumulation, cadmium levels in organs of cattle up to six years of age, ranged from 0.37-4.03 $mg \cdot kg^{-1}$ of fresh weight for kidneys and from 0.07 to 0.77 $mg \cdot kg^{-1}$ of fresh weight for livers. The maximum tolerated levels in one or both organs were exceeded in several scenarios. When considering organ excretion of cadmium, internal cadmium levels in organs were approximately one order of magnitude lower as compared to the results of the linear accumulation model. In this case only in the most extreme soil scenario, the maximum tolerated level in the kidney was exceeded. It was concluded that the difference between the two assumptions (linear model *versus* a steady state situation to estimate cadmium carry-over in cattle) is negligible in the animal's first five years of life, but will become relevant at higher ages. For the current case, the linear approach is a good descriptor for worst case situations. Furthermore, this study showed that quantitative supply chain modeling is an effective tool in assessing whether or not a specific combination of soil properties would lead to unacceptable contaminant levels in feedstuffs and animal products in the view of animal and human health.

Keywords. Feed safety, food safety, supply chain, feedstuffs, chemical contaminant, heavy metals, cadmium, modeling, carry-over, cattle organs.

1. INTRODUCTION

The supply of safe feed products to animals is crucial not only to safeguard animal health and welfare but also to reduce human exposure to potentially toxic compounds (PTC) like heavy metals and organic contaminants. Carry-over of PTC from feed into consumable animal products, like liver, kidney and muscles (meat), can contribute substantially to human intake of these compounds, particularly in case of heavy metals like cadmium. Therefore, legislative maximum limits have been set within the EU for a number of PTC, including heavy metals, in animal feedstuffs (2002/32/EC) and animal derived food products (2001/466/EC). To comply with these limits, control in every stage of the feed supply chain is needed, starting at the initial source of contamination and covering all other relevant stages of the feed chain. The number of relevant processes and stages depends on the particular contaminant of concern. For heavy metals, "control" already starts at the soil and/or water resources. Obviously, intensive monitoring of the safety of all parts of the feed and food chain, from the soil up to the feedstuffs and animal derived food products, is very cost- and labour-intensive. Knowledge of transfer processes of specific PTC through the feed and food chain offers a way to optimize monitoring activities and/or reduce their costs. Supply chain models, thereby, can help the development of intervention measures to control the contamination of PTC in the final feed and food products and can be used to assess the effectiveness of these control measures (Römkens et al., 2008; van der Fels-Klerx et al., 2008; van Raamsdonk et al., 2009). Obviously, such a modeling approach should include all stages of the supply chain of interest, including different contamination pathways and carry-over coefficients.

Heavy metals, such as cadmium (Cd), zinc (Zn), copper (Cu) and lead (Pb), are a group of PTC that are of concern when dealing with the quality of animal feedstuffs, particularly roughage. In the Kempen area of the Netherlands as well as in other European countries diffuse pollution of Cd has resulted in elevated levels in the soil. The presence of Cd in soils used for the production of feedstuffs results in high levels in the feed product due to uptake by the plant and consecutive accumulation in edible plants parts and in animals (Rietra et al., 2007). The degree to which Cd is available for plant uptake and further transfer into the feed chain strongly depends on the degree of pollution and soil characteristics. Hence, regional differences in soil Cd levels and soil characteristics will result in differences in contamination levels of plants used for feed production. In the animal's body, Cd may accumulate in the organs and/or be excreted by products like milk, meat and eggs and by the animal's metabolism. The extent of deposition and elimination in the animal depends on the half-life time of the compound and the period considered.

This study aimed to use supply chain modeling to estimate Cd levels in animal feed and animal organs in different scenarios related to soil characteristics and assumptions regarding Cd accumulation in the animal. As a case, the model was applied to cattle aged up to six years, which were fed roughage and compound feed.

2. MATERIALS AND METHODS

2.1. Model overview and scenarios

A supply chain model that links Cd in the soil to Cd in animal organs has been developed with the aim to estimate Cd levels in these animal derived food products. The model takes into account soil Cd levels, soil pH, soil-to-plant transfer, animal consumption patterns, and transfer into liver and kidneys. A schematic overview of the model is presented in **figure 1**.

The model was applied to cattle from 0 to 6 years of age, which were fed roughage, including maize and grass, and compound feed. Cadmium content in roughage and Cd intake by cattle were calculated for six different soils, as presented in **table 1**. These soil scenarios reflect the range of Cd in the soil and soil pH for acid sandy soils in the Kempen area in The Netherlands. The elevated Cd levels in soil are due to diffuse pollution from Cd and Zn smelters both in The Netherlands and in Belgium.

Table 1. Soil scenarios related to initial cadmium (Cd) level and soil pH used in this study.

Soil scenario	**Soil Cd level** (mg·kg^{-1})	**Soil pH**
A	0.5	4.5
B	0.5	5.5
C	1	4.5
D	1	5.5
E	2.5	4.5
F	2.5	5.5

Two different model approaches were applied to calculate the carry-over of Cd from intake into the cattle organs. The first one is a linear (irreversible) accumulation model which calculates the final Cd level in the organs based on a linear bioconcentration factor considering the total accumulated Cd intake. The second one is a non-linear steady-state model that also considers excretion of Cd and the development of a steady state situation. By definition, daily Cd intake equals daily elimination by metabolism and/or by excretion at steady-state. Differences between the two carry-over models were compared in terms of final Cd levels in the cattle organs (liver, kidney) maintaining all other model inputs equal. The two carry-over models were applied to each soil scenario, resulting in 12 different scenarios.

2.2. Model description

The supply chain model consists of two modules: the soil-plant module and the animal module. The soil-plant module calculates Cd concentrations in plants based on the soil Cd level, soil pH, organic matter and clay content. The animal module first calculates the total daily and annual Cd intake by animals considering the intake of roughage (grass and maize), compound feed, water and soil. Differences in the consumption patterns of younger and older cows are considered. Subsequently, the levels of Cd in liver and kidney are calculated based on either the linear bioconcentration model assuming accumulation only or the non-linear accumulation-excretion model. Below a summary of both modules is given; more details can be found in Franz et al. (2008) and Römkens et al. (2008).

Soil-plant module. First of all, Cd levels in grass and maize were calculated using an extended Freundlich equation that considers differences in Cd in soil, organic matter, clay and soil pH according to:

$$log[Cd_{plant}] = Constant + a \cdot log[organic\ matter] + b \cdot log[clay] + c \cdot log[Cd_{soil}] + d \cdot [pH] \qquad (1)$$

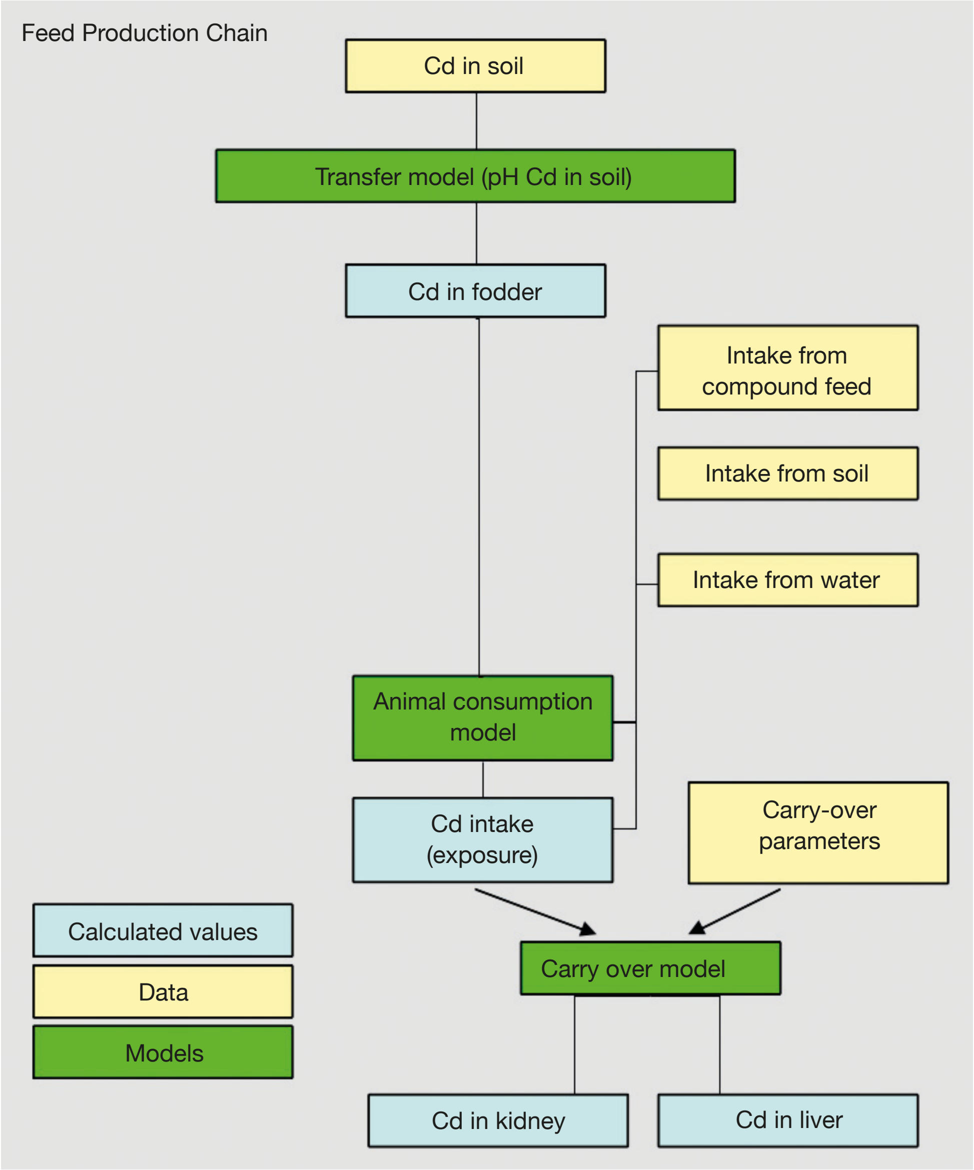

Figure 1. Schematic overview of the supply chain model of Cadmium.

with both Cd levels in the plant (Cd_{plant}) and Cd levels in the soil (Cd_{soil}) expressed in mg·kg^{-1} of dry matter. Freundlich equations have been used previously to successfully predict metal levels in crops like wheat (Adams et al., 2004) and rice (Römkens et al., 2009). Both organic matter and clay are expressed as percentage, and were fixed at 3% based on measurements in the Kempen area. Cd_{soil} and pH were grouped into the six scenarios presented in **table 1**, and are representative for non-polluted, slightly polluted and moderately polluted soils typically for this region. The soils are predominantly sandy with a low clay and organic matter content. The parameters of the regression coefficients a, b, c, and d were estimated based on regression analyses of field data (Römkens et al., 2007). The resulting coefficients used in equation 1 are presented in **table 2**.

Table 2. Regression parameters used for grass and maize to estimate cadmium levels in plants*.

Crop	Constant	a	b	c	d
Grass	1.45	0	0	1.22	- 0.38
Maize	0.90	0	- 0.32	1.08	- 0.21

*derived from Römkens et al. (2007).

Animal module

Animal intake. The daily Cd intake of cattle (DI in mg Cd per day) was calculated as the sum of the intake of soil, roughage (including grass and maize in a fraction of 70 to 30%), and compound feed, each of the three multiplied by their respective Cd contamination levels, see Equation (2).

$$DI = \sum (Cd_{soil} \times Co_{soil}) + (Cd_{compound} \times Co_{compound}) + (Cd_{roughage} \times Co_{roughage}) \quad (2)$$

The intake of water was proven to be negligible based on measurements of Cd in drinking water (Römkens et al., 2007). Cd levels in the soil (Cd_{soil}), in compound feed ($Cd_{compound}$) and in roughage ($Cd_{roughage}$) are expressed in mg per kg dry matter. Co_{soil}, $Co_{compound}$ and $Co_{roughage}$ represent the animal daily consumption of respectively soil, compound feed and roughage, expressed in kg dry matter per day. Soil ingestion (Co_{soil}) was assumed to be due to soil attached to roughage and was fixed at the level of 3% of total grass and maize consumption. Soil Cd contamination levels (Cd_{soil}) were based on the six scenarios (**Table 1**).

In The Netherlands, raw material for the production of compound feed is mainly imported, rather than produced locally. Therefore, levels of Cd in compound feed ($Cd_{compound}$) were based on monitoring results as stored into a database with the results of national monitoring programs on chemical contamination levels in feed and food products and their commodities (Van Klaveren, 1999). Based on this database, the median Cd level in compound feedstuffs was 0.05 mg per kg dry matter. Cadmium levels in grass and maize ($Cd_{roughage}$) were estimated using the soil-plant module.

The average daily intake of cattle was calculated for three age groups, being: 0-1 year, 1-2 years and > 2 years. Intake of grass, maize and compound feed in these three age groups was based on Römkens et al. (2007). For total roughage intake ($Co_{roughage}$), it was estimated to be 4, 8, and 14 kg dry matter per day. This resulted in an average daily intake for the three age groups of, respectively, 0.12, 0.24 and 0.42 kg of dry matter per day for soil; 2.8, 5.6 and 9.8 kg of dry matter per day for grass; and 1.2, 2.4 and 4.2 kg of dry matter per day for maize. Consumption of compound feed ($Co_{compound}$) was estimated to be 0.24, 0 and 2.32 kg of dry matter per day for the three age groups, respectively.

Carry-over. Carry-over of Cd to cattle animal organs (kidney and liver) was modeled according to two different approaches: one based on linear accumulation in target organs and one assuming the development of a steady state situation using an exponential accumulation-excretion model (Römkens et al., 2008). In case of linear accumulation, Cd irreversibly accumulates in the cattle liver and kidneys; there is no excretion from these target organs. This has been supported by several studies on Cd accumulation in organs of sheep (Loganathan et al., 1999) and cattle of 2.5 to 8 years of age (Olsson et al., 2001). The accumulation-excretion hypothesis on the other hand is also supported by several studies, *e.g.* by those for Cd in kidneys of cattle (Smith et al., 1991; Underwood et al., 1999). It has been suggested also that accumulation and excretion depend on the level of exposure or the age of the animals. For example, lower excretion rates were observed in sheep at an age between 3 and 28 months at higher exposure levels (Lee et al., 1996). Data of Spierenburg et al. (1988) for cattle can be described with a linear model until an age of up to five years old (Römkens et al., 2008), but at higher ages the accumulation levels tend to decrease, which favors the application of an exponential model. Excretion of Cd by urine was also found in cattle*, e.g.* by Smith et al. (1991).

The irreversible transfer of Cd into kidneys and liver in the linear accumulation model is calculated using a biotransfer rate (BTR). The BTR is defined as the increase of the Cd concentration in the organ tissue per day divided by the additional Cd intake per day, and expressed per 1 kg of tissue. Rates for the BTR used are 9.0×10^{-5} for kidneys and 1.7×10^{-5} for liver (Franz et al., 2008). The linear BTR model applied is represented in Equation (3):

$$C_t = BTR \times DI \times t \quad (3)$$

with C_t representing the Cd concentration in the organ (in $mg \cdot kg^{-1}$) after a period of t (days).

In case of the development of a steady state situation, Cd not only accumulates in the target organs but is excreted as well. In this case, the relationship between Cd intake and Cd levels in the organs is not linear but described by an exponential model. For all routes (accumulation and elimination) the concentration at day t can be described as follows:

$$C_t = C_o \cdot e^{-\lambda . t} + C_{SS} \cdot (1-e^{-\lambda . t}) \quad (4)$$

For which applies:

$$C_{SS} = BTF \cdot D \quad (5)$$

and $D = DI \times F_{abs}$

with C_t: concentration of contaminant ($mg \cdot kg^{-1}$) at day t, C_0: concentration of contaminant ($mg \cdot kg^{-1}$) at day 0, the starting level of the simulated period of time, C_{SS}: steady state concentration ($mg \cdot kg^{-1}$), λ: elimination time constant (1 per day), to be calculated from the half life time $T_{1/2}$, with $\lambda = \ln(2) / T_{1/2}$, *BTF*: biotransformation factor ($day \cdot kg^{-1}$), *D*: daily total uptake ($mg \cdot day^{-1}$), F_{abs}: absorption in the alimentary canal (%).

The BTF in (5) is defined as the constant to calculate the steady state concentration ($mg \cdot kg^{-1}$) from the uptake ($mg{\cdot}day^{-1}$) and has, therefore, the unit $day{\cdot}kg^{-1}$. The biotransformation factor BTF for accumulation in an organ is calculated as follows:

$$BTF = \frac{COR}{W{\cdot}\lambda} \qquad (6)$$

with *COR*: carry-over rate to the target organ (no dimension), *W*: weight of the organ (kg), λ: elimination time constant (1 per day).

In this study, an absorption factor (F_{abs}) of 20% (van Raamsdonk et al., 2007), a carry-over rate (*COR*) of 0.079% and a half-life time ($T_{1/2}$) of 900 days for kidneys was applied (van Raamsdonk et al., 2007). Comparable carry-over rates are reported by Neathery et al. (1975) and Kreuzer (1986). Adjusted to an absorption factor of 100%, the *COR* equals 16×10^{-5} (0.016%), which is comparable to the BTR used.

3. RESULTS

Estimated Cd levels in roughage and the estimated total Cd intake of cattle are presented in **table 3** for each of the six soil scenarios. The estimated Cd levels in roughage ranges between 0.16 and 1.50 $mg{\cdot}kg^{-1}$ at 12% moisture for maize and between 0.09 and 1.47 $mg{\cdot}kg^{-1}$ at 12% moisture for grass, depending on the soil scenario. Only in the most extreme scenario (scenario E: Cd soil level of 2.5 $mg{\cdot}kg^{-1}$ and pH of 4.5), Cd in roughage exceeded the EC maximum tolerated level (1 $mg{\cdot}kg^{-1}$ at 12% moisture, see 2002/32/EC). The total Cd uptake by the cow is dominated by grass consumption in each scenario.

The estimated Cd levels in the cattle organs are presented in **table 4** for each of the six soil scenarios and the two carry-over scenarios. Assuming linear accumulation during a life span of six years, Cd levels in cattle organs range from 0.37-4.03 $mg{\cdot}kg^{-1}$ of fresh weight (FW) for kidneys and from 0.07 to 0.76 $mg{\cdot}kg^{-1}$ of FW for livers. The maximum tolerated levels for both organs were exceeded in the most extreme soil scenario (scenario E). The maximum tolerated level in kidneys was also exceeded in two other scenarios (scenarios C and F).

Assuming excretion from the organs, Cd levels in the cattle organs after six years are approximately a factor two lower as compared to applying a linear

Table 3. Estimated cadmium levels in roughage and total cadmium intake by six-year old cattle in each of the six soil scenarios.

Soil scenario	**Cadmium content roughage** ($mg{\cdot}kg^{-1}$ at 12% moisture)			**Total cadmium intake cow** (in g per cow)		
	Maize	**Grass**	**Soil**	**Grass**	**Compound feed**	**Soil**
A	0.26	0.21	0.31	4.1	0.5	0.4
B	0.16	0.09	0.19	1.7	0.5	0.4
C	0.56	0.48	0.66	9.5	0.5	0.7
D	0.34	0.20	0.41	4.0	0.5	0.7
E	1.50 *	1.47 *	1.77	29.2	0.5	1.9
F	0.92	0.61	1.11	12.2	0.5	1.9

* Estimated value exceeds maximum tolerated level (1 $mg{\cdot}kg^{-1}$ at 12% moisture)

Table 4. Estimated cadmium intake and cadmium levels in organs (liver and kidney) of six year old cattle in the six soil scenarios and two carry-over scenarios.

Soil scenario	**Cadmium intake** (mg per day)	**Cadmium in kidney** ($mg{\cdot}kg^{-1}$ FW)		**Cadmium in liver** ($mg{\cdot}kg^{-1}$ FW)	
		linear	**exponential**	**linear**	**exponential**
A	3.4	0.66	0.32	0.13	0.06
B	1.9	0.37	0.18	0.07	0.03
C	7.2	1.42 *	0.69	0.27	0.13
D	3.8	0.75	0.36	0.14	0.07
E	20.5	4.03 *	1.96 *	0.76 *	0.37
F	10.4	2.05 *	1.00	0.39	0.19

* Estimated value exceeds maximum tolerated level (1.0 $mg{\cdot}kg^{-1}$ FW for kidney and 0.5 $mg{\cdot}kg^{-1}$ FW for liver).

model. Only in the most extreme scenario (scenario E) the maximum level in the kidney was exceeded.

4. DISCUSSION AND CONCLUSION

The difference between the two approaches, linear *versus* exponential modeling in estimating carry-over of Cd by cattle is small during the animal's first five years, but will become relevant at higher ages. Since we consider a cattle productive life span of six years which is about two times the contaminant biological half-life time (900 days), the linear approach is a good descriptor for worst case situations in this study. However, for those situations where estimated levels of cadmium equal or exceed legal limits, more precise estimations are required.

It can be calculated that, approximately, 97% of the steady-state-level is reached after five times the half-life time of the contaminant. In the case of Cd this situation will never been reached, because of the assumed (very) long half-life time.

The half-life time for Cd in kidneys as used in the exponential model results from fitting the model to the data of Spierenburg et al. (1988), see **figure 2**. Using a BTR of 2 × 10^{-4} (Römkens et al., 2008) or a COR of 0.12% (absorption factor of 20%, see van Raamsdonk et al., 2007), linear and exponential models describe the data of Spierenburg et al. (1988) equally well for all data points younger than five years. Therefore the most simple, *i.e.* linear model, can be chosen. The difference between the models increases rapidly at higher ages. Olsson et al. (2001) fitted a linear relationship between cattle age and Cd levels in the kidney, with age running up to 12 years. They found a yearly increase of about 26 mg·kg^{-1} Cd in the kidney. However, the percentage of explained variance of the linear model was low, which may have been due to data related to the older ages. An exponential approach will give a more realistic description at cattle above five years of age.

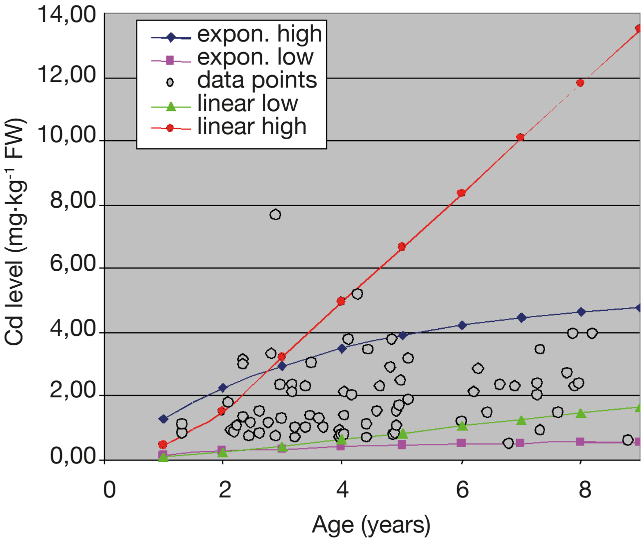

Figure 2. Cd levels in cattle kidneys from the Kempen area in relation to their age. Data from Spierenburg et al. (1988) with only data points up to nine years old shown. The highest and lowest exposure scenarios are shown, calculated with a linear model (straight lines) and with an exponential model (curved lines).

This study shows that quantitative supply chain modeling is an effective tool to estimate contaminant levels in feedstuffs and animal products. It enables the user to assess whether or not a specific combination of soil properties, soil acidity and land use leads to unacceptable levels of animal exposure in view of product quality and human health. The model can be used for a relatively fast evaluation of cadmium exposure for specific regions, without the necessity of setting up extensive soil and crop monitoring schemes. Based on initial model assessment, monitoring can focus on those areas where product quality is expected to exceed legal limits for Cd in both animal fodder and products for human consumption. Due to the limited number of model parameters the model is also easy to adapt to other regions and/or other contaminants. This facilitates the harmonization of risk assessment procedures considerable and will help to overcome apparent differences in legal limits in soil which do exist at present.

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