Not peer-reviewed

Prediction of changes in soil cadmium contents at EU and Member State (MS) level

Paul Römkens, Wageningen University and Research, The Netherlands

Erik Smolders, KU Leuven, Belgium

The impact of levels of cadmium (Cd) in mineral phosphorus (P) fertilisers on long term (100 years) Cd accumulation in arable soil across EU-25 (=EU-28-CY, MT, HR) was evaluated using a revised model for calculating heavy metal balances in soils. This revision relates to an improved sub-model to calculate leaching of Cd from soil incorporated in the existing INTEGRATOR modelling framework of Wageningen Environmental Research (De Vries et al 2011). INTEGRATOR is able to calculate spatially explicit changes for nutrients and heavy metals including Cd at variable scale levels. The revised leaching model was developed recently (2018) by scientists from KU Leuven and Wageningen Environmental Research. The revised model not only combines source data from both models used previously, it also represents a single unified model. This revision was undertaken since previous results by Smolders (2017) and by Römkens et al. (2017, concept paper) revealed that leaching is the dominant output of Cd from soil, but also that calculated leaching fluxes were the main reason for uncertainty in the computed changes of Cd in soil by either model.

Here we assess the long term (100 year) impact of applying Cd fertilisers with Cd levels ranging from 20 ('Cd20' scenario), 40 ('Cd40' scenario) to 60 ('Cd60' scenario) mg Cd kg^{-1} P_2O_5 on the average changes in soil Cd contents. In these scenarios it is assumed that all mineral fertilisers contain the same amount of Cd in all countries at the level of the scenario (i.e. 20, 40 or 60 mg Cd kg^{-1} P_2O_5). In addition, a 100 year simulation of application of current levels of Cd via mineral fertilisers is included (Business as Usual, **'BaU'**). For the BaU scenario we used documented MS level specific data on Cd in mineral fertilisers as published by Smolders (2017). Details of the calculations will be included in a more in-depth report and paper currently (May 17, 2018) being prepared.

In addition to the previous studies from Smolders (2017) or Römkens et al. (2017), **an uncertainty analysis** is performed. The revised model used to calculate leaching by definition still has a degree of statistical uncertainty (as is the case for any model: we have not sampled all individual soils of EU), and this will cause a band-width surrounding the predicted average soil Cd content at EU level at any given point in time. This level of uncertainty in predicted Cd contents in soil has been quantified using a Monte Carlo simulation technique (i.e. performing a large number of model runs with randomly generated model parameters, details to be included in the report and paper) thus assessing the uncertainties both at EU-25 level and MS level. This analysis is used to assess for which MS (or the EU as a whole) predicted average changes in soil Cd are significant; here we use a level of <5% probability of making the wrong prediction as the indicator of significance, also interpreted as >95% certainty of making the right prediction of the trend. The uncertainty analysis of the trends in soils Cd is not the same as the analysis of the spatial variation, we clarify.

- **Analysis of spatial variability**: the trends shown in the analysis by Smolders (2017) showed, at each proposed Cd limit in the fertiliser, a range of trend above and below the average point, that "error bar" denoted the variability depending on the soil type. This variability is now more precisely encapsulated in this new model based on the EU-wide spatial explicit information, such as climate, animal manure, fertiliser use and crop yield and is shown as a band width in Fig.1a below.

- **Analysis of model uncertainty**: identifying the statistical uncertainty surrounding a predicted trend, here: the trend of the EU average soil Cd contents or a MS average soil Cd contents, this analysis is give as a band-width in Fig. 1b below and shows the upper and lower intervals beyond which likelihood is less than 5% on both sides.

Results of the predicted changes of Cd in arable soils (average and analysis of variability) reveal that:

1. Cadmium in soil changes depending on the level of Cd in fertiliser, the average change of the soil Cd content at EU level at t=100 years compared to the current situation ranges from -5% (depletion) in case of the Cd20 scenario to +3.2% in case of the Cd60 scenario (figure 1a, left panel).
2. Predicted absolute changes at EU level in soil Cd after 100 years are small, on average less than 0.02 mg kg^{-1} in either scenario (figure 1a, right panel).
3. Regional differences are substantially larger and, at NUTS3 level (regional level, approx. 1200 units in the EU), predicted changes in the average soil Cd range from -0.15 mg kg^{-1} to + 0.07 mg kg^{-1} (compared to the EU average soil Cd content at t=0; figure 1a right panel).
4. For Cd an approximate average equilibrium in soil (i.e. soil Cd at t=100 is equal to at t=0) is calculated if the average Cd content in mineral P fertilisers is equal to **44 mg Cd kg^{-1} P_2O_5**.

The uncertainty analysis reveals that

1. Using the 95% criterion for significance, predicted relative changes in average soil Cd at EU level within the range of 20 to 60 mg Cd kg^{-1} P_2O_5 are not significantly different from zero, in other words, model uncertainty is such that the predicted average change in soil Cd at EU-25 level in all three scenarios (Cd20 to Cd60; figure 1b) is not statistically different from the current soil Cd content.
2. At MS level, changes in soil Cd for the three scenarios are, however, significant for a number of MS. These are summarized in tables 1 and 2 in the section below.
3. A shift from BaU to the Cd20 scenario would, at MS or at EU level not lead to a significant change in soil Cd except for GR where accumulation, under the BaU is not significant anymore compared to the BaU scenario.
4. A shift from BaU to Cd60 would results in a significant degree of accumulation in 3 MS (from 'yellow' to 'red' in table 2); it also causes a reversal of the trend from depletion to accumulation – for 7 MS – even though the degree of accumulation does not meet the 95% criterion (from 'green' to 'yellow' in table 2)
5. Only if Cd in mineral fertilisers were to be reduced to zero there is a significant effect on the average soil Cd content at EU-25 level in that we can say with 95% accuracy that the average soil Cd content will decrease compared to the current soil Cd content.

Illustration of results and details for the calculations

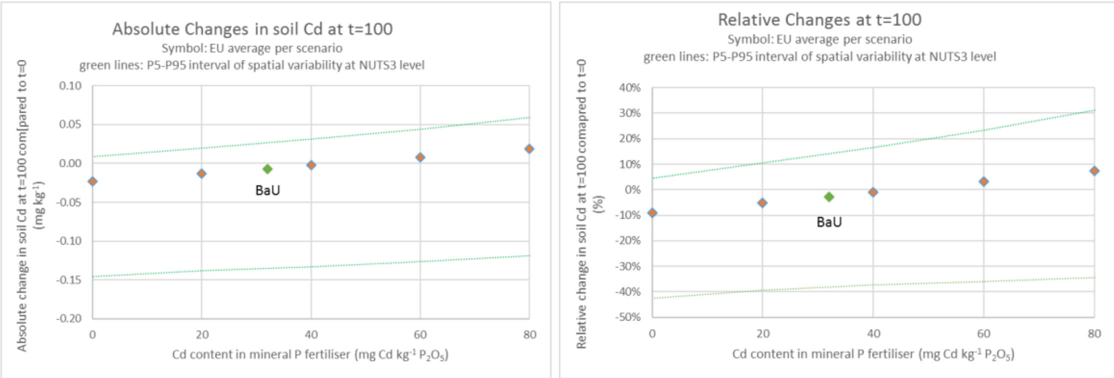


Figure 1a. Effects of spatial variability on the trend: absolute (left) and relative (right, compared to Cd in soil at t=0) EU-average change in soil Cd content for arable soils after 100 years for the Cd20 to Cd60 and the BaU scenario (symbols). To illustrate the degree of spatial variability that occurs at regional level, the P5 – P95 interval of results at NUTS3 level are included.

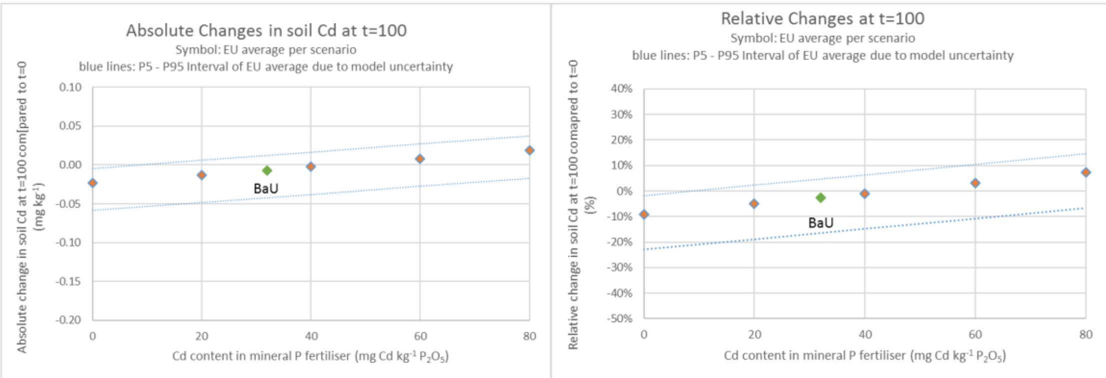


Figure 1b. Effects of model uncertainty on the trend. Absolute (left) and relative (right, compared to Cd in soil at t=0) EU-average change in soil Cd content for arable soils after 100 years for the Cd20 to Cd60 and the BaU scenario (symbols). Green lines reflect the P5 – P95 range due to model uncertainty in the leaching flux of Cd from soils.

Prediction of changes in soil cadmium at MS level

The model not only generates average results at EU-25 level as discussed above, it also generates results at MS or regional level; here we summarize some of the major findings at MS level. Like the analysis at EU level, changes in the average Cd content at MS level are considered *significant* if the predicted changes are larger than the ones at t=0 (accumulation) or lower than at t=0 (depletion) with <5% probability of making a wrong prediction. Table 1 below results are shown for those countries and scenarios that meet the <5% error criterion (the predicted average Cd content at MS level indicate that Cd at t=100 > Cd at t=0 with >95% precision) or depletion (the predicted average Cd content at MS level indicate that Cd at t=100 < Cd at t=0 with less with >95% precision).

Table 1. List of countries where the MS average soils with have accumulation or depletion in 100 years (with <5% probability of incorrect conclusion) under the Cd20, C40 and Cd60 scenario respectively

Level of Cd in mineral P fertilisers	Cd in soil will accumulate	Cd in soil will decrease
Cd20	ES	AT, BE, CZ, DK, FL, IE, LU, NL, SE, SL
Cd40	EE, ES, GR, HU	BE, CZ, DK, IE, LU, NL, SE, SL
Cd60	EE, ES, GR, HU, IT	LU, SE, SL

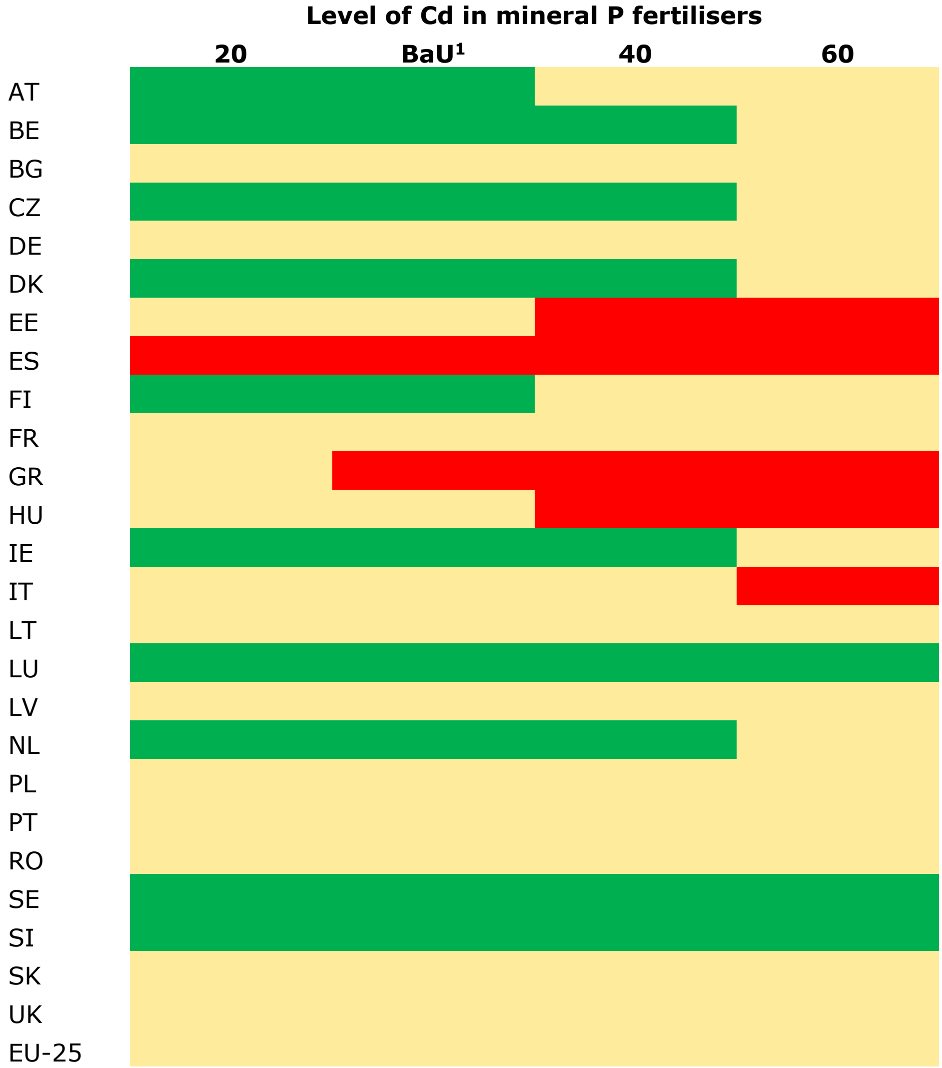
For some countries not mentioned in this table, the <5% error level is never met under the scenarios listed, i.e. the changes in soil Cd are too small and not statistically >0 or <0 with 95% precision (i.e. net trend too uncertain to mention). This is illustrated in table 2 below with colour coding.

Green: under the given scenario model results are such that with 95% accuracy we can state that Cd in soil will decrease (comparing levels of Cd in soil at t=100 and t=0)

Red: under the given scenario, model results are such that, with 95% accuracy we can state that Cd in soil will accumulate (comparing levels of Cd in soil at t=100 and t=0)

Yellow: model uncertainty is such that we cannot, with 95% accuracy, state that Cd in soil will either accumulate or decrease.

Table 2. Overview of accuracy at MS level that Cd in soil will either accumulate (red: more than 95% certain) or decrease (green: more than 95% certain). Yellow fields indicate that the changes in soil Cd are too small and not statistically >0 or <0 with 95% precision (i.e. net trend too uncertain to mention)



[1] Business as usual, same input as in 2010 (specific for each MS, using MS data for Cd in mineral P fertilisers from Smolders, 2017)