INTRODUCTION

Traditional models for long-timescale dose assessment are generally conceptually simple, featuring one, two or three spatial compartments in the soil column with annually averaged parameters. The soil-plant system is usually modelled using a simple concentration ratio (CR). The justification is that timescales relevant to geologic disposal of radioactive waste are so long that simple models are necessary to account for the inherent uncertainties over the timescale of the dose assessment. However, with detailed site characterisation relevant to licensing-stage dose assessments this simple approach may be seen to have important shortcomings, particularly in the case of long-term accumulation of radionuclides in natural ecosystem with rapid transition to agriculture.

Kłos et al. (2011), Pérez-Sánchez et al. (2012), Kłos et al. (2014) and Pérez-Sánchez & Thorne (in press) have recently developed and refined higher spatial and temporal resolution models: ten layers in the soil column with varying $k_{ds}$ linked to soil conditions and monthly rather annually averaged parameters allow variability of the water table position and redox sensitive radionuclides to be directly addressed. Soil-plant interactions are treated as a dynamic process, allowing for root uptake according to the crop's root profile.

The recent publications have focused mainly on the distribution of radionuclides in the soil column. Here, attention focusses on soil-plant interaction in agricultural soils employing a variant of the ten-soil layer, monthly varying model, GEMA-10, described by Kłos et al. (2014). Results suggest that where transient processes are important a simple interpretation of the soil-plant concentration ratios may not reliably reflect plant concentration necessitating a better conceptual framework.

MATERIALS AND METHODS

Uptake by plants grown on the soil can be calculated by either a concentration ratio or as a dynamic uptake process with two interpretations of the uptake rate $\lambda_p\text{ year}^{-1}$, consistent with the interpretation
of soil-plant concentration ratio, \( CR \) (Bq kg\(^{-1}\) fw)(Bq kg\(^{-1}\) dw), as used by Avila et al. (2010); Hjerpe & Broed (2010) and Pérez-Sánchez et al. (2012).

\[
\lambda_{ip}^n = s_i^n \frac{r_{ip} m_i f_i}{\Delta z_i (1 - \varepsilon_i) \rho_i} CR, \quad s_i^n = \left\{ \begin{array}{ll}
1 & \text{uptake from whole compartment} \\
\theta_i^n + (1 - \varepsilon_i) \rho_i k_i^n & \text{uptake from porewater only}
\end{array} \right.
\]

The thickness of the soil layer is \( \Delta z_i \) m, with root fraction \( r_{ip} \) (unitless), standing biomass \( m_i \) kg m\(^{-2}\) and annualised fractional growth rate in month \( n \), \( f_i \) year\(^{-1}\). Bulk density of the soil layers takes into account the porosity of the layer, \( \varepsilon_i \) (unitless) and the grain density of the solid material, \( \rho_i \) kg m\(^{-3}\). Klos & Wörman (2013) introduced the factor \( s_i^n \) to distinguish uptake from the total inventory in the soil layer from uptake from inventory in soil solution only. In the latter case the factor depends on the soil layer’s monthly averaged volumetric moisture content \( \theta_i^n \) (unitless). The \( k_d \) in each layer (\( k_i^n \) (Bq kg\(^{-1}\) dw)(Bq m\(^{-3}\))\(^{-1}\)) is determined as monthly values allowing for changes in redox conditions due to changes in \( \theta_i^n \). Annual and monthly averaged data for precipitation and ETP are used, leading to variations in the water table height. Both interpretations are consistent with the understanding of \( CR \) but the latter accounts for the fact that plant roots see the solute concentration, not the whole inventory (including that bound to solids. \( CR \) measurements use the bulk soil concentration (whole inventory).

The soil column is assumed to be 2 m deep with ten equal layers and the crop is winter wheat. The crop modelled is winter wheat, harvested in July. Numerical data are taken from Kłos et al., (2014). As a control for the advanced model, a “standard” two compartment model with annual average hydrological data and using the concentration ratio was also calculated. "Top soil" is the upper 40 cm and "deep soil" the lower 140 cm (cf Pérez-Sánchez, et al., 2012). The models were implemented in Ecolego.

RESULTS AND CONCLUSIONS

For an initial inventory of 1 Bq of each of \(^{79}\text{Se}\) (weakly sorbing high soil-plant CR), \(^{129}\text{I}\) (moderately sorbing) and \(^{226}\text{Ra}\) (strongly sorbing, low CR) in the upper 20 cm of the soil column. The models calculate inventories in each of the soil layers and the plant.

Figure 1 shows evolution of \(^{79}\text{Se}\) soil and plant inventories during the first 10 years using alternatives of spatial resolution (2 compartment vs 10 compartment models) and \( CR \) and dynamic root uptake. Selenium is strongly redox sensitive and this is reflected in the variation in topsoil (top 40 cm) and deep soil (lower 160 cm) inventories. The ten-layer model with annually averaged data reflects this but the “standard” 2-compartment model with annualised data underestimates the top soil inventory (Figure 1c). This carries over into the plant inventory (Figure 1a). There is more rapid loss from the soil-plant system in the case of the low resolution model. Using the \( CR \), the plant inventory is higher using the 10-layer model than when the same soil model is used with the dynamic uptake form the whole compartment using the above expression for \( \lambda_{ip}^n \) (whole inventory). The full monthly resolution model for the plant inventory (Figure 1b) suggests that the annualised model might underestimate the content of the plant at harvest. In this case the dynamic model gives the highest response by a factor of less than two compared to the \( CR \) approach but a factor of over four compared to the “standard” approach shown in Figure 1(a).
Figure 1. Dynamics of the soil-plant system, $^{79}$Se. Top, using annual averages for ten- and two-compartment models, comparing CR and dynamic uptake. Middle, ten-compartment model with monthly averages. Corresponding soil inventories are shown below with different temporal and spatial resolution models.

Figure 2. Alternative interpretations of plant inventory for $^{79}$Se, $^{129}$I and $^{226}$Ra. The “standard model” (2-compartment, annual, CR) gives consistently lower uptake and dynamic uptake higher. The potential influence of soil $k_d$ is seen with several orders of magnitude higher uptake in the case of $^{226}$Ra.

Figure 2 shows results for each of the radionuclides in comparison to the “standard” 2-compartment model. Three methods of determining the peak plant inventory are used with the 10-layer model with monthly data: CR relative to the top soil concentration and the two versions of $\lambda_{ip}^n$ above. If it is assumed that the value of the CR is related to availability in soil solution (as described by the variant for $\lambda_{ip}^n$) the potential for higher crop concentrations for a given soil inventory implies appreciably higher plant maxima. For moderate to high $k_d$ ($^{129}$I and $^{226}$Ra) inventories can be many orders of magnitude higher than calculated by the “standard model”. Higher spatiotemporal resolution models suggest that plant content will be higher than lower resolution models when using the method for deriving root uptake rates employed by Avila et al. (2010), Pérez-Sánchez et al. (2012) and Hjerpe & Broed (2010).
In the long term, for chronic inputs to the agricultural system, these differences of interpretations may not have much influence on dose; however, it is precisely this transient regime with initial inventories of accumulated radionuclides in new agricultural soils that are of concern, particularly in the Fennoscandian and the use of the best practicable representation of the soil-plant system in evaluations of dose is required. Similar concerns might apply to remediated land in the NORM context.

Results here suggest that higher spatiotemporal resolution models can capture important features of the transient regime following the commencement of agriculture on contaminated land. A better understanding of the soil-plant uptake rate is required. This would involve a clearer experimental description of the dynamics of plant uptake and this should be linked to the soil hydrogeochemistry and the transport processes in plants. There are potential inconsistencies in the use of the CR to derive \( \lambda_p \) here. Pérez-Sánchez & Thorne (in press) have noted that equilibrium plant concentrations derived from models using this method do not correspond to the originating CR values. The inclusion of the factor to distinguish between whole inventory and soil-solution models of dynamic root uptake emphasises that the modeller needs to be aware of the local spatiotemporal conditions under which the CR are obtained. The plant transpires the soil solution, not the whole inventory. Work is currently in progress with GEMA-10 to try to resolve these issues and to improve the implementation of dynamic crops in assessment models.

ACKNOWLEDGEMENT

This work has been supported by the Swedish Radiation Safety Authority (SSM), and the Empresa Nacional de Residuos Radiactivos (ENRESA) under agreement CIEMAT/ENRESA. However, the opinions expressed are those of the authors and do not necessarily represent those of the supporting organizations.

REFERENCES


Klos, RA and Wörman A (2013) Uncertainties in doses from agricultural ecosystems following conversion from wetlands 2013, Proceedings of the 14th International High-Level Radioactive Waste Management Conference (IHLRWMC), American Nuclear Society
