SUPPORTING INFORMATION

Identification of dissipation pathways for pharmaceuticals in batch experiments with natural soils – A modelling approach

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Prior parameter distributions for the calibration

Table S1 Prior Parameter distributions for calibrations that are equal for all substances[1] .

Parameter name	Initial value	Transformation type	Distribution type	a	b
a [d^{-1}]	0.064	10^{-x}	Gamma	2.2	1
D [m^2 d^{-1}]	1E-11	10^{x}	Normal	-11	1
g [-]	1.5	x	Normal	1.5	0.2
r [m]	1E-5	-	-	-	-

Details of model alternatives

The following model alternatives were considered and analyzed but rejected in favour of the chosen version.

1. Instead of defining NER as the pharmaceutical concentrations in the most inner shells, NER is defined as a separate pool, similar to TM in the reference model, and formed from the RES fraction instead following first order kinetics.

$$\frac{1}{n_{shells}}\frac{dS_1}{dt} = \alpha\left(K_f C_W^m - S_1\right) - d_1(S_1 - S_2) - k_{NER}S_1 \#(1)$$

$$\frac{1}{n_{shells}}\frac{dS_2}{dt} = d_1(S_1 - S_2) - d_2(S_2 - S_3) - k_{NER}S_2 \#(2)$$

$$\frac{1}{n_{shells}}\frac{dS_i}{dt} = d_{i-1}(S_{i-1} - S_i) - d_i(S_i - S_{i+1}) - k_{NER}S_i \#(3)$$

$$\frac{1}{n_{shells}}\frac{dS_{n_{shells}}}{dt} = d_{n_{shells}-1}\left(S_{n_{shells}-1} - S_{n_{shells}}\right) - k_{NER}S_{n_{shales}} \#(4)$$

[1]a and b indicate the Distribution parameters. In the case of normal distribution, a and b are equal to median and standard deviation. Parameters without a transformation and distribution are considered constant and not calibrated.

$$\frac{dNER}{dt} = \sum_{i=2}^{n_{shales}} S_i \cdot k_{NER} \#(5)$$

2. Similar to model alternative 1, the NER fraction of the compound is considered as a separate pool, but the kinetics is here driven by equilibration towards an equilibrium following a simple linear equilibrium model between shells and the NER-pool.

$$\frac{1}{n_{shells}} \frac{dS_1}{dt} = \alpha\left(K_f C_W^m - S_1\right) - d_1(S_1 - S_2) - k_{NER}(S_1 - NER) \#(6)$$

$$\frac{1}{n_{shells}} \frac{dS_2}{dt} = d_1(S_1 - S_2) - d_2(S_2 - S_3) - k_{NER}(S_2 - NER) \#(7)$$

$$\frac{1}{n_{shells}} \frac{dS_i}{dt} = d_{i-1}(S_{i-1} - S_i) - d_i(S_i - S_{i+1}) - k_{NER}(S_i - NER) \#(8)$$

$$\frac{1}{n_{shells}} \frac{dS_{n_{shells}}}{dt} = d_{n_{shells}-1}\left(S_{n_{shells}-1} - S_{n_{shells}}\right) - k_{NER}\left(S_{n_{shales}} - NER\right) \#(9)$$

$$\frac{1}{n_{shells}} \frac{dNER}{dt} = \sum_{i=2}^{n_{shales}} \left(S_i - NER\right) \cdot k_{NER} \#(10)$$

3. Based on Zarfl 2009 *et al,* all processes are considered as first order kinetics [1]. Formation of RES from NER is reversible. Formation of NER and TM is irreversible. NER and TM are both formed from EAS:

$$\frac{dEAS}{dt} = -EAS \cdot \left(k_{RES} + k_{TM} + k_{NER}\right) + RES \cdot k_{EAS} \#(11)$$

$$\frac{dRES}{dt} = -RES \cdot k_{EAS} + EAS \cdot k_{RES} \#(12)$$

$$\frac{dTM}{dt} = k_{TM} \cdot EAS \#(13)$$

$$\frac{dNER}{dt} = k_{NER} \cdot EAS \#(14)$$

4. The dataset on sulfadiazine (SDZ) fate in soils by Förster et al. includes measurements of two different transformation products, OH-SDZ and Ac-SDZ, which are formed from the active parent compound SDZ inside the organism [2]. OH-SDZ is assumed to represent the fraction TM while, under environmental and thus experimental conditions, the metabolite Ac-SDZ is considered to revert back to SDZ.

$$\frac{dC_W}{dt} = -\alpha\left(K_f\left(C_w\frac{\rho}{\theta}\right)^m - S_1\right) - k_{TM}C_W + k_{AcSDZ}C_{AcSDZ} \#(15)$$

$$\frac{dC_{AcSDZ}}{dt} = -k_{AcSDZ}C_{AcSDZ} \#(16)$$

where k_{AcSDZ} $[T^{-1}]$ is the transformation rate constant from Ac-SDZ to SDZ and C_{AcSDZ} is the concentration of Ac-SDZ $[MM^{-1}]$.

Estimation of the extraction error

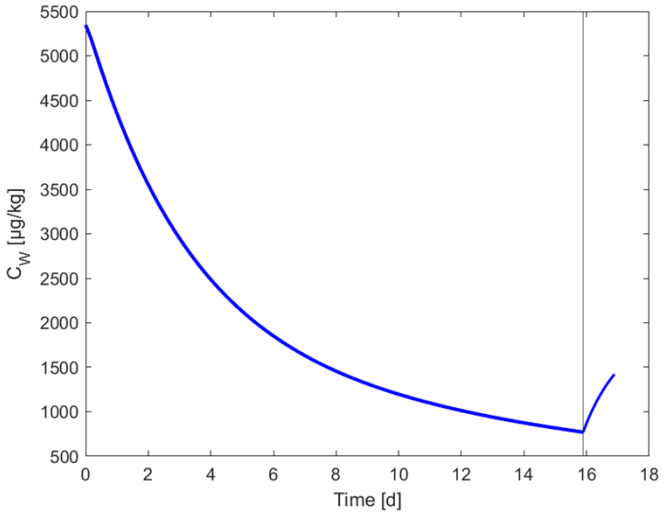

Figure S1 Simulated extraction of sulfamethoxazole from a sterile soil. The blue line indicates the pollutant mass in the water per soil mass. Start of extraction is simulated approximately at day 16, indicated by a vertical line.

Correlation between extraction bias and determined parameter values

Table S2 Correlation between selected[2] parameters and the extraction bias

	m	
	Coefficient	**p-value**
Pearson	0.82	0.00
Spearman	0.42	0.15
Kendall	0.39	0.08

Speciation of pollutants under environmental pH

Table S3 Speciation of pollutants at a soil pH of 6.8-7.5

Pollutant	**Cationic fraction**	**Neutral fraction**	**Anionic fraction**
Bezafibrate	-	0	1
Carbamazepine	-	1	0
Ciprofloxacin	0.03-0.16	0.82-0.89[3]	0.01-0.07
Diclofenac	-	0	1
Naproxen	-	0	1
Sulfadiazine	0	0.09-0.32	0.68-0.93
Sulfamethoxazole	0	0.01-0.06	0.94-0.99
Trimethoprim	0.33-0.72	0.28-0.67	-

Comparison of calibration results and extraction error

[2] Only parameters that showed a significant correlation ($p<0.05$) to the extraction error for at least one test are shown.

[3] In the case of ciprofloxacin, "neutral" refers to the net ionic charge consisting of a cationic and an anionic charge.

Table S4 NRMSE between the simulated "undisturbed" aqueous concentration and the simulated extracted concentration of antibiotics in sterilized and non-sterilized soils.

Sorbate	NRMSE Zarfl2009	NRMSE calibration	$NRMSE_{extract}$ extraction error
Bezafibrate non-sterile	0.31	0.25	0.03
Bezafibrate sterile	0.28	0.13	0.04
Carbamazepine non-sterile	0.22	0.28	0.47
Carbamazepine sterile	0.08	0.21	0.50
Ciprofloxacin non-sterile	0.14	0.23	0.90
Diclofenac non-sterile	0.12	0.22	0.05
Diclofenac sterile	0.27	0.17	0.05
Naproxen non-sterile	0.14	0.26	0.06
Naproxen sterile	0.11	0.19	0.12
Sulfamethoxazole non-sterile	0.19	0.17	0.02
Sulfamethoxazole sterile	0.21	0.16	0.02
Trimethoprim non-sterile	0.31	0.22	4.27
Trimethoprim sterile	0.28	0.25	12.15
Average	0.19	0.21	-

Sensitivity and uncertainty analysis

The tables show averaged activity scores over all datasets of one data source (see Table S5-8). The values show the relative sensitivity of the mass fraction to the respective input parameter. All values are in a range between 0 and 100 and are rounded to whole numbers.

Table S5 Averaged activity scores for the Dalkmann datasets under sterile conditions[3] The values show the relative sensitivity of the respective simulated pollutant fraction (EAS, RES, TM, NER) to the respective input parameter. All values are in a range between 0 and 100 and are rounded to whole numbers.

	EAS	**RES**	**NER**
$\alpha\ [d^{-1}]$	25	6	12
$D\ [m^2 d^{-1}]$	14	92	97
$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$	18	6	2
$m\ [-]$	62	24	11
$\boldsymbol{g}$ **[-]**	0	0	0
$\beta\ [-]$	29	1	0

Table S6 Averaged activity scores for the Sittig datasets. The values show the relative sensitivity of the respective simulated pollutant fraction (EAS, RES, TM, NER) to the respective input parameter. All values are in a range between 0 and 100 and are rounded to whole numbers.

	CW	**EAS**	**RES**	**NER**	**TM**
$\alpha\ [d^{-1}]$	5	69	44	19	0
$D[m^2 d^{-1}]$	3	8	18	69	5
$k_{TM}\ [d^{-1}]$	100	29	73	37	100
$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$	3	33	18	1	0
$m\ [-]$	4	55	30	3	0

Table S7 Averaged activity scores for the Förster datasets. The values show the relative sensitivity of the respective simulated pollutant fraction (EAS, RES, NER, TM-OH, TM-AC) to the respective input parameter. All values are in a range between 0 and 100 and are rounded to whole numbers.

	EAS	**RES**	**NER**	**TM-OH**	**TM-AC**
$\alpha\ [d^{-1}]$	2	22	43	11	0
$D\ [m^2 d^{-1}]$	0	0	0	0	0
$k_{TM,OH}\ [d^{-1}]$	88	11	10	84	0
$k_{TM,AC}\ [d^{-1}]$	16	1	1	6	100
$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$	5	28	28	22	0
$m\ [-]$	11	62	72	39	0

Determined parameter values and confidence intervals

The following tables show the 2.5%, 50% and 97.5% confidence intervals of the posterior distribution of the parameters after calibration. All parameter values apply to the data under sterile and non-sterile conditions except the rate constant for transformation and mineralization k_{TM}, which is zero for all sterile datasets, and ciprofloxacin, where no sterile dataset was available.

Table S8 Results of bootstrapping for the datasets by Dalkmann et al. Bootstrap samples are created by resampling the observed data with replacement. Confidence intervals refer to the parameters calibrated to the bootstrap samples. All values smaller than 1E-03 are displayed as zero, except values for the dispersivity D.

	$\alpha[d^{-1}]$			$D[m^2 d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Bezafibrate	1.3E-03	9.4E-03	2.9E-01	1.0E-15	1.8E-15	3.6E-15
Carbamazepine	0E+00	1.3E-03	9.2E-02	8.3E-18	1.7E-17	3.7E-17
Ciprofloxacin	0E+00	1.4E-01	7.6E-01	1.8E-16	6.4E-16	8.9E-15
Diclofenac	0E+00	2.6E-02	1.8E-01	6.4E-14	2.1E-13	2.5E-04
Naproxen	0E+00	3.2E-02	8.5E-01	2.0E-16	3.3E-16	2.0E-15
Sulfamethoxazole	3.1E-03	3.4E-02	9.4E-02	1.6E-14	3.3E-14	6.2E-13
Trimethoprim	0E+00	0E+00	1.0E-01	4.0E-25	2.2E-18	1.7E-17

	$\beta[-]$			$k_{TM}[d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Bezafibrate	5.6E-01	1.1E+00	2.4E+00	3.7E-03	9.3E-03	2.5E-02
Carbamazepine	4.8E-01	1.6E+00	5.3E+00	2.2E-05	2.2E-05	2.2E-05
Ciprofloxacin	1.2E+00	2.6E+00	5.8E+00	2.6E-06	2.2E-04	8.6E-04
Diclofenac	4.2E-01	1.1E+00	3.5E+00	1.6E-02	1.7E-01	5.2E-01
Naproxen	2.7E-01	7.9E-01	2.7E+00	2.0E-03	2.0E-03	2.0E-03
Sulfamethoxazole	1.0E+00	1.9E+00	3.4E+00	1.0E-07	2.7E-03	4.5E-03
Trimethoprim	1.3E+00	4.0E+00	1.9E+01	4.5E-07	7.3E-04	1.3E+00

	$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$			$\left(\frac{\mu g}{kg}\right)m[-]\left(\frac{\mu g}{kg}\right)$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Bezafibrate	7.3E+00	1.6E+01	2.3E+01	5.9E-01	7.7E-01	8.7E-01
Carbamazepine	1.2E+00	3.3E+00	2.0E+01	8.6E-01	1.1E+00	1.5E+00
Ciprofloxacin	2.6E-01	2.1E+04	6.7E+04	3.9E-01	2.1E+00	3.3E+00
Diclofenac	2.3E+00	1.0E+01	3.0E+01	7.8E-01	9.7E-01	1.5E+00
Naproxen	2.3E+00	1.1E+01	2.3E+01	6.9E-01	7.9E-01	1.0E+00
Sulfamethoxazole	9.3E+00	2.7E+01	6.5E+01	5.9E-01	7.2E-01	8.8E-01
Trimethoprim	7.9E+00	2.1E+01	7.1E+01	9.3E-01	1.3E+00	2.4E+00

	$g[-]$		
Percentiles	**2.5%**	**2.5%**	**2.5%**
Bezafibrate sterile	5.1E-01	6.1E-01	1.3E+00
Carbamazepine	5.2E-01	6.9E-01	1.1E+00
Ciprofloxacin	1.0E+00	1.3E+00	2.0E+00

Diclofenac	5.0E-01	7.1E-01	1.2E+00
Naproxen	5.1E-01	6.7E-01	9.6E-01
Sulfamethoxazole	5.0E-01	7.0E-01	1.3E+00
Trimethoprim	5.0E-01	5.8E-01	1.2E+00

Table S9 Results of bootstrapping for the datasets by Sittig et al. Bootstrap samples are created by resampling the observed data with replacement. Confidence intervals refer to the parameters calibrated to the bootstrap samples.

	$\alpha[d^{-1}]$			$d[m^2 d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	3.1E-03	2.0E-02	1.0E-01	4.8E-13	1.0E-11	3.3E-09
Sulfadiazine 2	4.7E-03	1.8E-02	5.7E-02	7.7E-13	8.6E-12	1.7E-08
Sulfadiazine 3	2.9E-03	1.9E-02	5.9E-02	1.7E-13	5.5E-12	4.6E-08

	$g[-]$			$k_{TM}[d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	4.6E-01	1.4E+00	2.1E+00	4.5E-05	4.5E-05	1.1E-02
Sulfadiazine 2	7.7E-01	1.4E+00	2.0E+00	4.5E-05	4.5E-05	1.4E-03
Sulfadiazine 3	4.6E-01	1.4E+00	2.0E+00	4.5E-05	4.5E-05	1.7E-03

	$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$			$m[-]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	1.1E-02	2.1E+00	4.9E+00	3.1E+01	5.3E-01	8.9E-01
Sulfadiazine 2	1.4E-03	2.3E+00	4.4E+00	3.1E+01	5.6E-01	9.3E-01
Sulfadiazine 3	1.7E-03	1.7E+00	4.6E+00	3.1E+01	6.0E-01	8.7E-01

Table S10 Results of bootstrapping for the datasets by Förster et al. Bootstrap samples are created by resampling the observed data with replacement. Confidence intervals refer to the parameters calibrated to the bootstrap samples.

	$\alpha[d^{-1}]$			$d[m^2 d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	1.1E-03	2.8E-02	6.6E-01	2.5E-14	3.7E-13	7.6E-10
Sulfadiazine 2	1.2E-03	1.3E-02	2.1E-01	7.1E-14	9.4E-13	8.7E-10
Sulfadiazine 3	2.3E-04	8.0E-03	3.3E-02	1.4E-14	1.9E-12	7.4E-11

	$k_{TM-OH}[d^{-1}]$			$k_{TM-Ac}[d^{-1}]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	4.5E-05	6.8E-03	1.1E-01	8.8E-02	1.4E-01	2.4E-01
Sulfadiazine 2	4.5E-05	4.5E-05	1.5E-02	1.4E-01	1.8E-01	2.7E-01
Sulfadiazine 3	1.1E-02	1.7E-02	4.3E-02	7.9E-02	2.3E-01	4.9E-01

	$K_f\left[\left(\frac{\mu g}{kg}\right)\left(\frac{L}{\mu g}\right)^m\right]$			$m[-]$		
Percentiles	**2.5%**	**50%**	**97.5%**	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	1.4E+00	5.4E+00	3.1E+01	6.7E-01	9.4E-01	1.0E+00
Sulfadiazine 2	1.5E+00	5.4E+00	3.1E+01	7.1E-01	9.4E-01	1.0E+00
Sulfadiazine 3	2.8E+00	4.8E+00	3.1E+01	7.2E-01	8.6E-01	9.9E-01

	$\beta[-]$		
Percentiles	**2.5%**	**50%**	**97.5%**
Sulfadiazine 1	7.1E-01	2.5E+00	1.4E+01
Sulfadiazine 2	9.7E-01	2.9E+00	1.4E+01
Sulfadiazine 3	1.6E+00	2.9E+00	1.9E+01

Shell distribution

The formation of NER is only dependent on the diffusivity and the number of shells that belong to RES and NER. Hence, the number of shells and the distribution between RES and NER is crucial for the processes described by the model. The distribution of shells changes only between the three data sources to reflect differences in the soils and extraction methods of each of the studies. To determine the ideal distribution of shells, the model is calibrated with the data from Sittig and Förster without the data about NER for different distributions of shells (Figure S2)[4]. The results are compared to the observed NER-data and the NRMSE between the observed and simulated values are calculated.

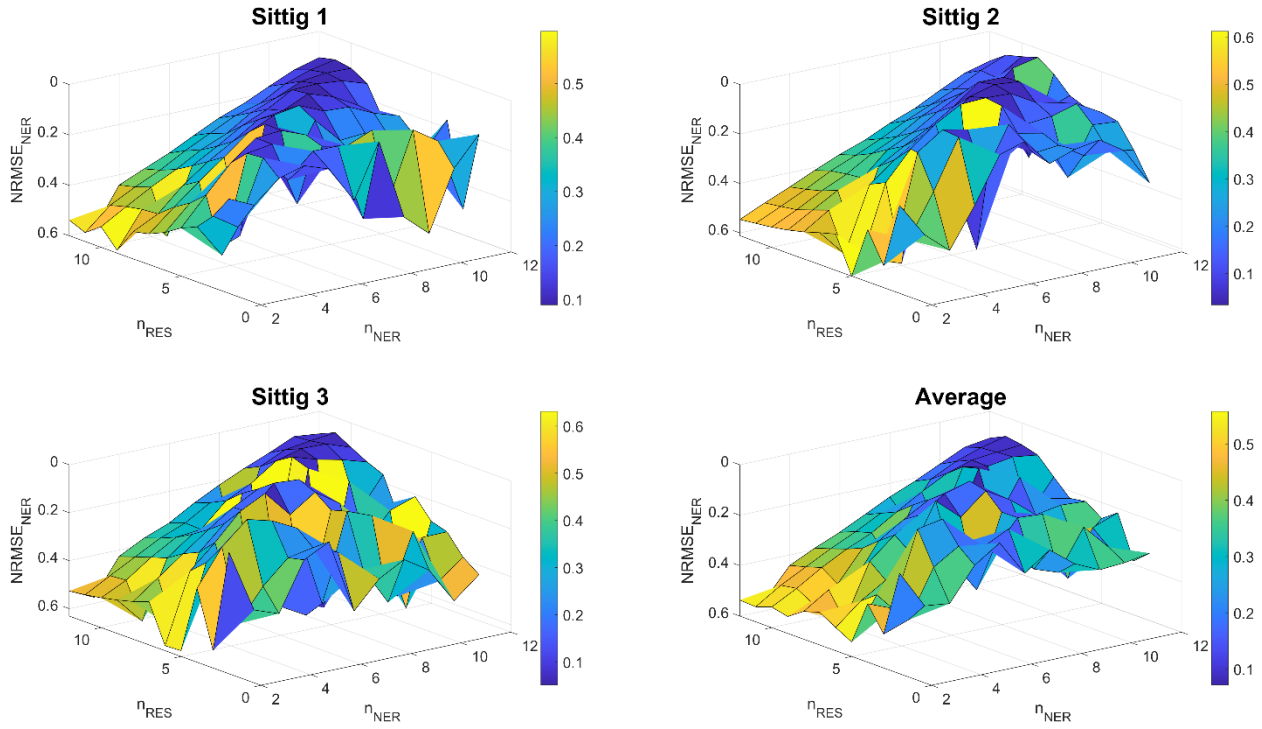

Figure S2 Overview of different shell distributions for all Sittig datasets. n_{RES} indicates the number of shells that are assigned to the RES-fraction, n_{NER} the number of shells assigned to the NER-fraction. $NRMSE_{NER}$ indicates the NRMSE between the simulated and observed NER-fractions. Observed NER-values were not considered for calibration in this case.

For the Sittig-dataset, the NRMSE values between simulated and observed NER-values are lowest if the numbers of RES and NER-shells are similar for all datasets. The distribution of shells was chosen accordingly (Table S11). This corresponds to the observed values of RES and NER, which had very similar values.

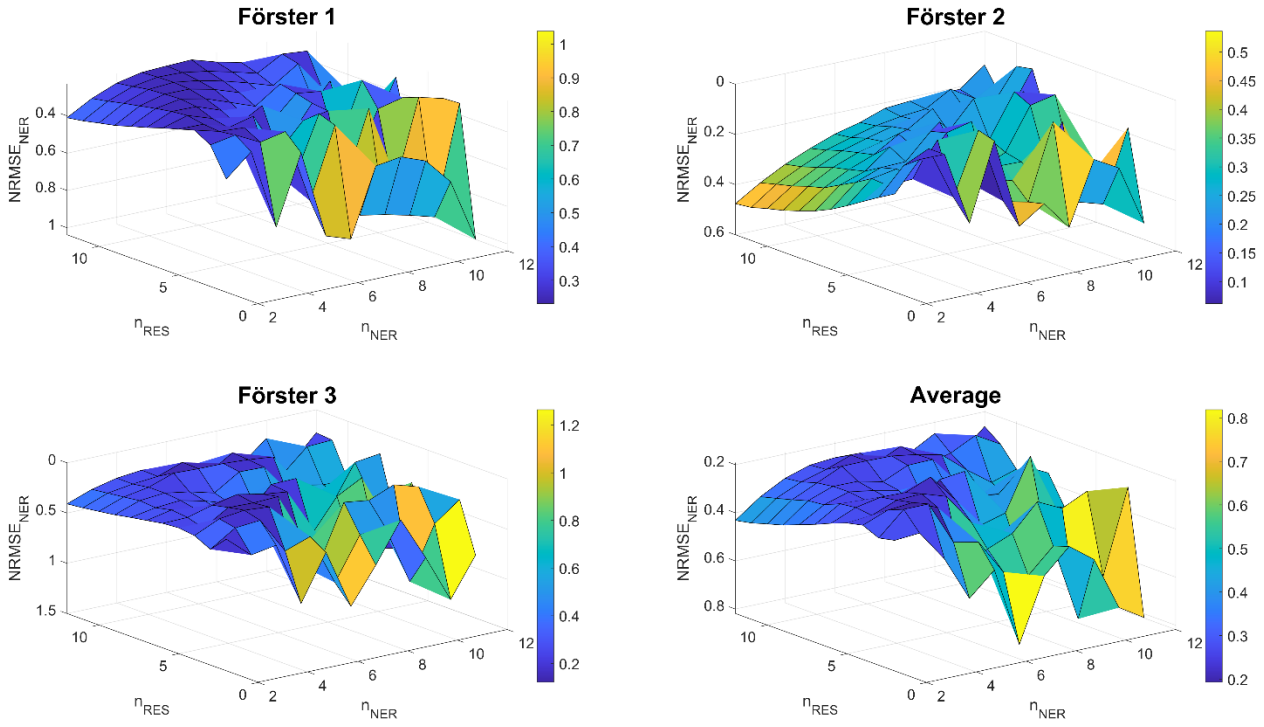

Figure S3 Overview of different shell distributions for all Förster datasets. n_{RES} indicates the number of shells that are assigned to the RES-fraction, n_{NER} the number of shells assigned to the NER-fraction. $NRMSE_{NER}$ indicates the NRMSE between the simulated and observed NER-fractions. Observed NER-values were not considered for calibration in this case.

The overall distribution of shells for the Förster-dataset looks very similar as for the Sittig-dataset (Figure S3). A similar amount of NER- and RES- shells leads to the lowest NRMSE. The Sittig- and Förster-datasets used soil from the same location and the same substance for experiments. Hence, a similar distribution of shells is to be expected. Unlike the Sittig-datasets, the NRMSE of the Förster-dataset does increase less if the number of RES-shells exceeds the number of NER-shells. This might be caused by the observation of TM in the Förster-dataset.

Therefore, the amount of NER is fixed even if it is not part of the fitting, since all mass is accounted for through EAS, RES and TM.

Table S11 Number of shells that are assigned to RES and NER

Data source	n_{RES}	n_{NER}
Dalkmann *et al.*	6	30
Sittig *et al.*	4	4
Förster *et al.*	6	6

References

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3 P. Dalkmann, C. Siebe, W. Amelung, M. Schloter and J. Siemens, Does long-term irrigation with untreated wastewater accelerate the dissipation of pharmaceuticals in soil?, *Environ. Sci. Technol.*, 2014, **48**, 4963–4970.

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