R-17

Development and Application of a One-Compartment Bioaccumulation Model for Disaggregating the Effect of Sediment Organic Carbon Content on Feeding Rate from the Effect on Toxicant Bioavailability in the Mudworm (*Lumbriculus variegatus*)

by Larry E. Fink, Private Consultant,
Boynton Beach, FL

Abstract

The mudworm (*Lumbriculus variegatus*) was selected to evaluate the bioavailability of first-flush methylmercury (MeHg) in peat soils from the proposed footprint of the ~30,000-acre storage reservoir complex in the Everglades Agricultural Area in South Florida. To reduce the pre-bioassay MeHg concentration in a mudworm laboratory culture, it was switched from salmon to algae flake ration (0.0146 vs. ~0.004 mg/Kg MeHg wet weight). After 28 days of depuration, algae-fed mudworms contained more MeHg than expected. To identify the likely cause, a one-compartment mathematical model of uptake and depuration was constructed and solved analytically and dynamically using a 4th-order Runge-Kutta numerical integration algorithm. The ingestion rate was estimated by assuming mudworms consume dry-weight bioenergetically available carbon at a constant rate at a constant temperature.

Abstract
(continued)

This allowed adaptation of the literature value consumption rate for lake sediment to either salmon or algae flake ration in a bioenergetically self-consistent way. Based on published values of mudworm reference sediment consumption and growth rates and assumptions regarding bioenergetically available carbon content, the depuration half-life that produces a self-consistent result for both rations is in the range of 6 to 16 days. Significant carry-over of pre-test MeHg residue was thus unlikely. The model was able to reproduce the MeHg bioaccumulation trajectories for mudworms exposed to different lake sediments published by others without invoking differences in MeHg bioavailability. The modeling results suggest that bioaccumulation factors should be normalized to the contaminated medium consumption rate before evaluating the effect of organic carbon content or other factors on toxicant bioavailability.

Background

- See Poster R-18

Methods

- See Poster R-18

Study Design

- To evaluate MeHg first-flush potential, in Phase I 6, 4-cm core samples were obtained from each of 5, 200-acre subunits and composited for each of 50, 1,000-acre operational units (OUs).
- In Phase II, 10 of the 50 were randomly selected for a 28-day mudworm (*Lumbriculus variegatus*) bioassay with wet worm and wet soil analysis for THg and MeHg and wet soil analysis for ash, moisture, TFe, TS, TMn, AVS, THg and MeHg.

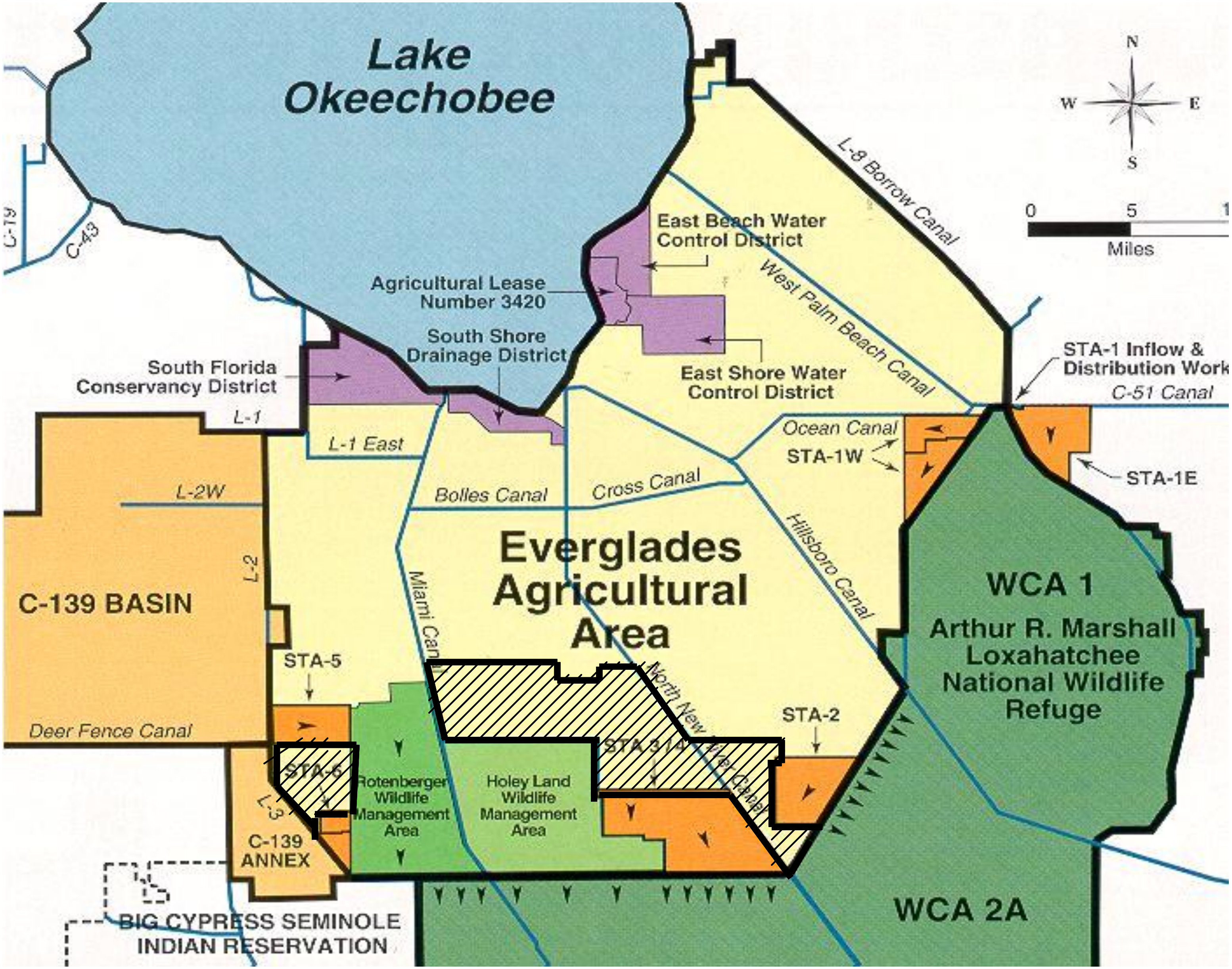


Figure 1. Proposed footprint of the Everglades Agricultural Area (EAA) Storage Reservoir Project (EAASRP)

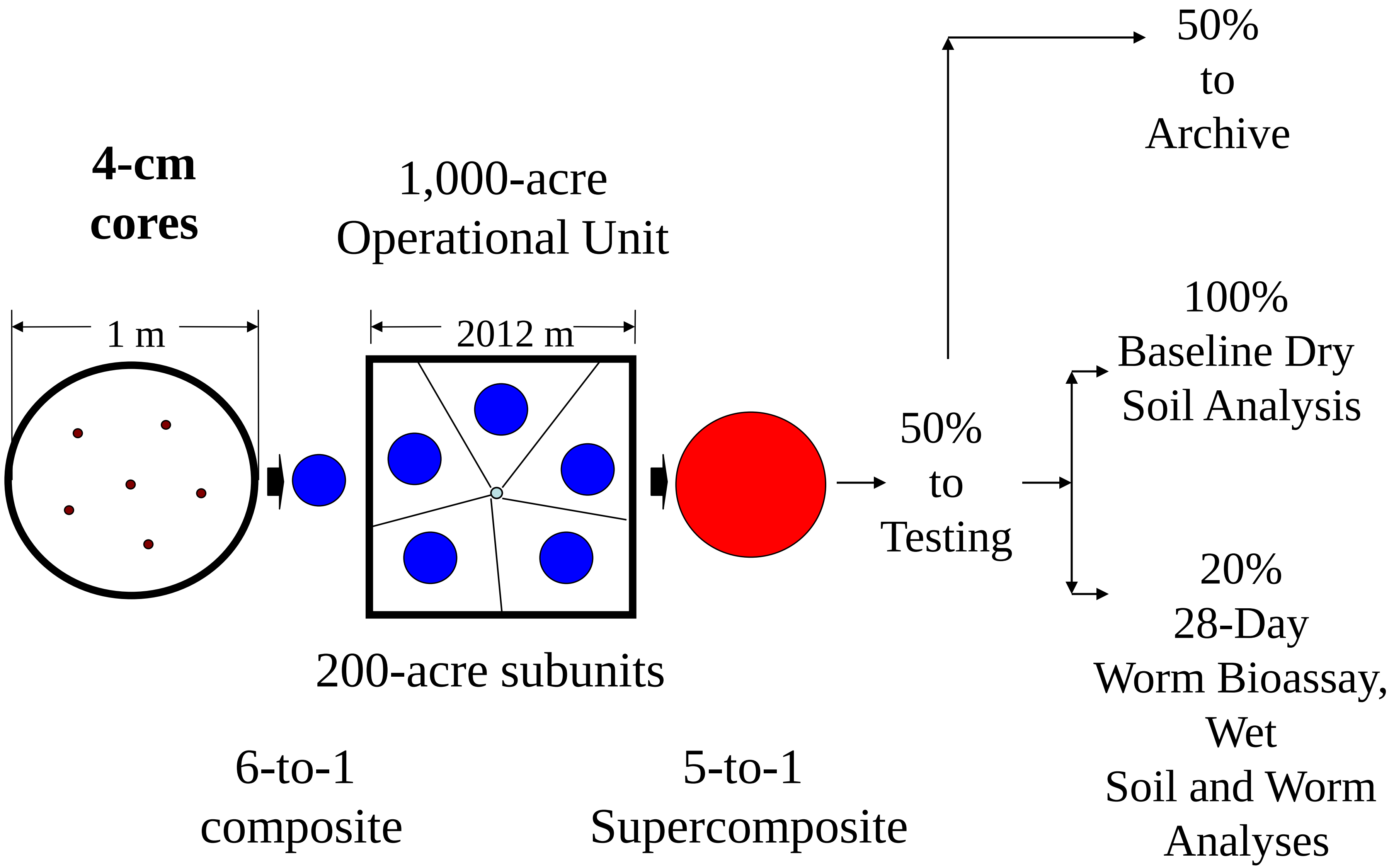


Figure 2. Soil Field Sampling and Sample Processing Protocol for the EAASRP

Problem

- t = 0 mudworm (n = 3) samples contained:

  THg = 0.0045 +/- 0.00013; MeHg = 0.004 +/- 0.00063 mg/Kg dry wt.

- Salmon flake (n = 1) sample contained:

  THg = 0.039; MeHg = 0.0165 mg/Kg dry wt.

- Relatively high concs. prompted switch to cleaner algae flake ration for 28 d depuration:

  THg = 0.0029; MeHg = ~0.005 mg/Kg dry wt.

- But, due to holding time issues, bioassay initiated w/o t = 0, algae-fed mudworm results.

Problem

- After 28-day depuration, algae-fed t = 0 mudworm MeHg decreased by only 55% to 0.0019 +/- 0.0002.
- If due to change in bioavailability, one would expect MeHg less bioavailable from algae than salmon ration, because salmon protein likely more readily digested than algae cellulose.
- If due to slow depuration and t=0 carryover to day 28, <u>bioassay results would be useless</u>.
- Mathematical model was needed to evaluate salmon ration- and algae ration-fed mudworm results in self-consistent way.

Model Development

- One compartment with oral uptake, depuration, and growth dilution only; pore water uptake assumed suppressed by binding to high DOC.
- Exposure can be delayed to mimic mudworm pre-burrowing acclimation period.
- Exact exponential solution for constant exposure, growth and depuration.
- Differential equation for variable exposure and/or growth, and/or depuration solved using 4^{th}-order Runge-Kutta algorithm.
- Algorithm verified vs. exact solution.

$$dCO/dt = CS(t) \times IR(t) \times AE - KD \times CO(t) - KG \times CO(t)$$

Where:

CO(t)	=	conc. toxicant in test organism (mg/Kg wet wt.) as function of time
CS(t)	=	conc. toxicant in sediment, soil, or ration (mg/Kg wet wt) as function of time
IR(t)	=	organism ingestion rate per unit wet body wt. as function of time
AE	=	toxicant absorption efficiency by gut (unitless)
KD	=	depuration rate coefficient (day-1)
KG	=	growth rate coefficient: 1/doubling time (day-1)

Model Parameterization

- Reference mudworm ingestion rate (~12X bw/day at 23^{0}C) and growth rate (pop. doubles ~8-12 days) obtained from Ingersoll et al., 1998.
- MeHg bioavailability from salmon and algae ration assumed to be 95% for initial model parameterization.
- Depuration half-life obtained via model calibration.

Initial Results

- Model could <u>not</u> reproduce both salmon flake- and algae flake-fed mudworm results using self-consistent parameter values, unless …
- … algae-fed mudworms were producing MeHg *in gastro* (i.e., abs. eff. > 100%) …
- … or $t_{1/2}$ in algae-fed >> than salmon flake-fed mudworms.
- Neither explanation seemed likely.
- However, if mudworm consumed more algae than salmon ration to meet bioenergetic demand for metabolism, growth, & reproduction, then self-consistent results might be obtained.

Model Reformulation

- Unfortunately, the USEPA 28-day mudworm bioassay does not require the use of a tracer or extrusion rate to infer the ration or test soil ingestion rate.
- To fill this critical data gap, the model was modified to adjust the reference sediment ingestion rate for <u>assumed</u> differences in bioenergetic value of the organic carbon on dry mass basis within a biomass and bioenergy balance framework.

$$IRTS = IRRS \times [RSfoc/TSfoc] \times [(1-RSm)/(1-TSm)] \times [RSbev/TSbev] \times [1-ROm]/[1-TOm]$$

Where:

IRTS, IRRS = ingestion rate of test ration, sediment, or soil and reference sediment, respectively.

RSfoc, TSfoc = fraction organic carbon of reference sediment and test ration, sediment, or soil, respectively

RSm, TSm = fraction moisture reference sediment and test ratio, sediment, or soil, respectively.

RSbev, TSbev = bioenergetic value of reference sediment and test ration, sediment, or soil to test organism, respectively.

ROm, TOm = fraction moisture of reference and test organisms, respectively

Doubling Time = TOfoc/(IRRS x TSfoc x TSbev x TOce)

Where:

TOfoc = test ration, sediment, or soil fraction organic carbon.

IRRS = test ration, sediment, or soil ingestion rate.

TSbev = bioenergetic value of test ration, sediment, or soil to test organism.

TOce = conversion efficiency of bioenergetically bioavailable organic carbon converted to test organism biomass.

Model Parameterization

- Unfortunately:

(1) the reference sediment and mudworm foc and moisture not reported by Ingersoll et al. (1998);

(2) bioenergetic values of salmon flake and algae flake to mudworm were not reported and could not be calculated from literature studies, …

- … so initial values had to be guesstimated based on typical ranges of values in the literature for similar organisms.
- Values then adjusted until bioenergetically self-consistent ingestion and growth rates obtained.

Model Parameterization

- Reference mudworm feeding rate (~12X bw/day at 23^0C) and growth rate (pop. doubles ~8-12 days) obtained from Ingersoll et al., 1998.
- Wet soil ash, moisture via lab analysis.
- Mudworm ash based on literature value from Hansen et al., 2002; FGS msd. moisture.
- Algae, salmon ration max. ash content obtained from vendors.
- Algae, salmon ration moisture assumed = reference sediment before mudworm accepts.

Results

- Using the modified model, algae- and salmon –fed mudworm IRs were calculated to be ~6 and 0.4 frac. bw/day, respectively, with a doubling time of 8 days,

when:

- RSfoc, Afoc, Sfoc = 0.035; 0.30; 0.47
- RSm, Am, Sm = 0.85; 0.85; 0.85
- RSbev, Abev, Sbev = 0.175; 0.04; 0.41
- ROm, TOm = 0.88; 0.88*
- TOfoc = 0.32
- TOce = 0.55

* measured value

Results

- Using self-consistent oc bioenergetic values for salmon and algae flake, calibrated $t_{1/2}$s were in range 6 to 16 days when ref. sed foc varied between 0.035 and 0.095 using realistic ranges of mudworm bioenergetic parameter values and AE = 95%. Best fit was $t_{1/2}$ = 16 d with 8-d doubling time and AE = 95%.
- Nuutinen (1999) reported $t_{1/2}$ values ranging from 4.3 d in sediment with 34% oc to 11 d in sediment with 3.5% oc, but $t_{1/2}$s of 6.6 and 5.3 d, respectively, when 5 and 20 mg/Kg Se added.
- No attempt here to relate ration Se to MeHg AE, because no analyses and/or too few samples.

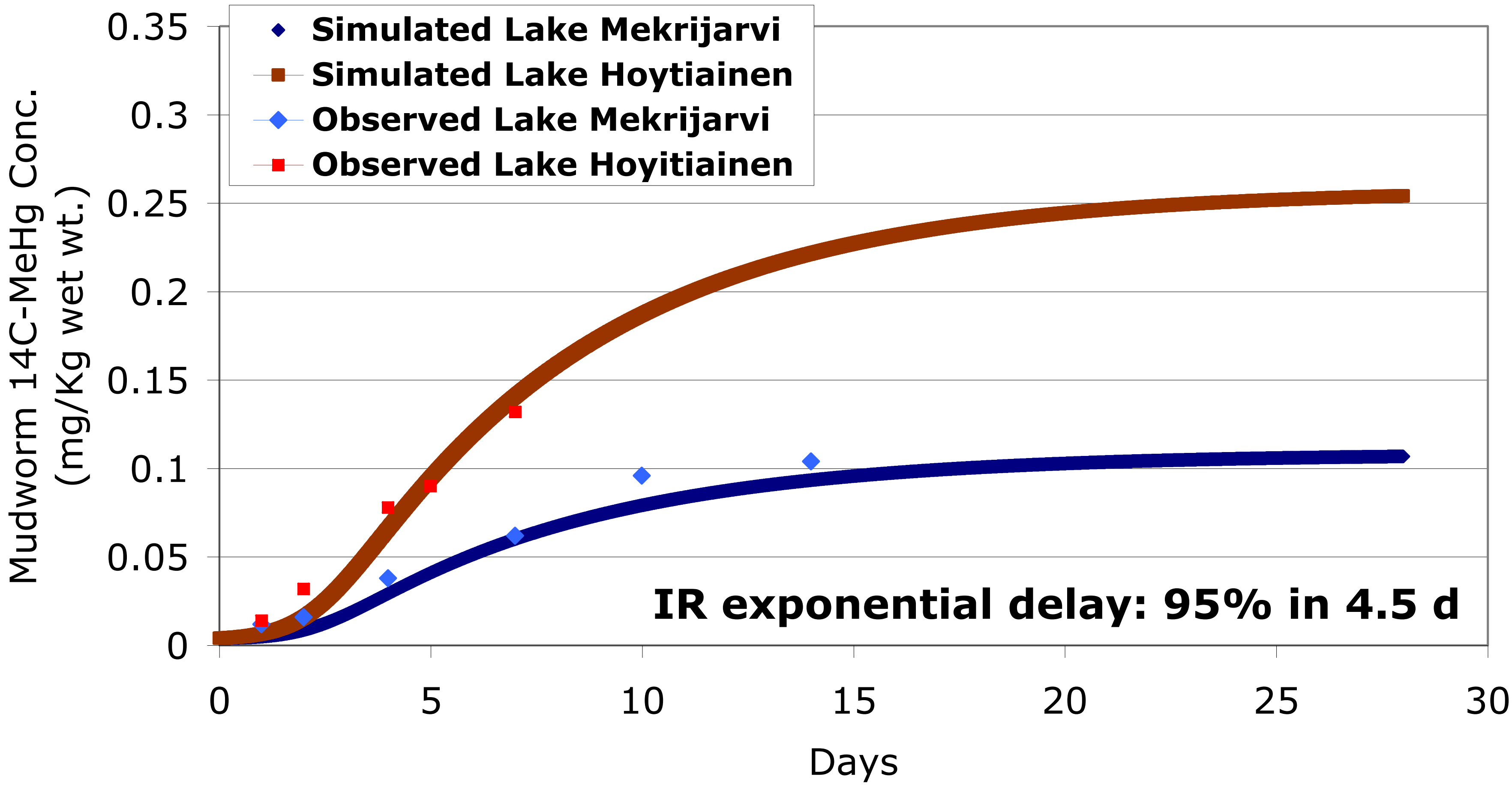
Results

- Nuutinen (1999) also reported sediment ingestion rates (Ks sed dw/g org ww/h, with the highest rate for sed. with lowest foc (0.023) and lowest rate with highest foc (0.353), but with variable results for intermediate foc values.
- No attempt to measure wet or dry organic carbon assimilation efficiency or wet or dry growth rate per unit assimilated wet or dry organic carbon.

Test of Model

- Model then applied to results of MeHg mudworm bioaccumulation study of two Finnish lakes (Nuutinen and Kukkonen, 1998).
- Authors concluded MeHg bioavailability was inversely related to sediment foc.
- However, if IRs adjusted to reflect differences in lake sed. foc and moisture, & use bioenergetics ref. sed. values, model calibrates to observed bioacc. data when: abs. eff. (AE) = 0.95; $t_{1/2}$ = 16 d; size doubles in 8 d with exp. delay in mudworm burrowing (95% at 4.5 d) (Fig 1)
- … better fit with size doubles in 12 d (Fig 2)

Simulated vs. Observed Mudworm Bioaccumulation in Finnish Lake Sediment:
MeHg AE = 0.95; KD = 0.693/16 d; KG = 1/8 d



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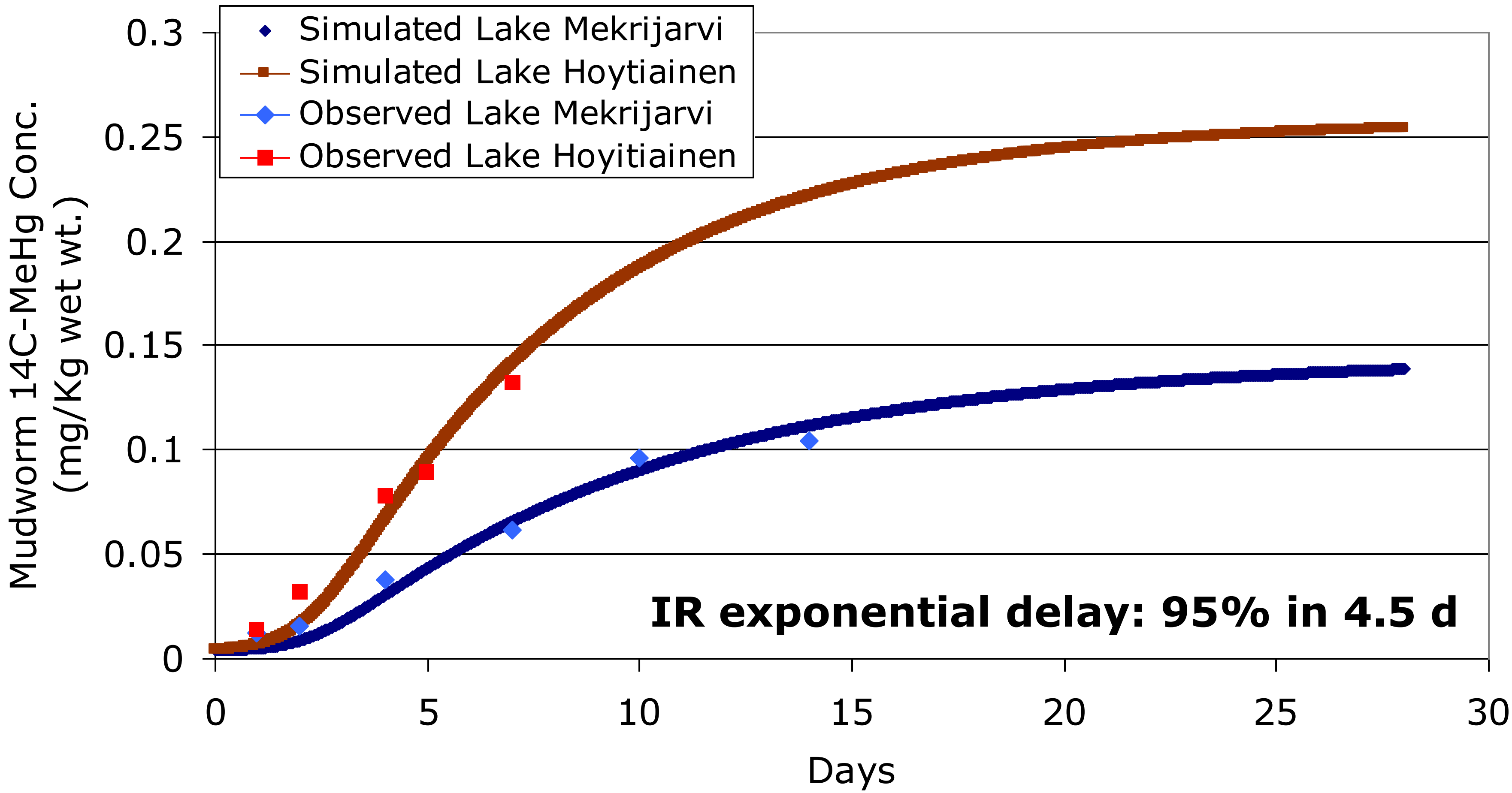

Key Findings

- A one-compartment model of mudworm uptake, depuration, and growth dilution, using published IRs, KGs, and $t_{1/2}$s and AE = 0.95 would not calibrate to both salmon and algae flake results.
- Model calibrates when modified such that IR reflects ration or medium organic carbon quantity and quality using published ranges of bioenergetics values.
- Best-fit model reproduces others' mudworm MeHg conc. trajectories with 4.5-d lag to max IR.
- … but model highly sensitive to bioenergetic parameter values and growth assumptions.

Conclusions

- The results of this exercise suggest one must disaggregate effect of ration, sediment, or soil foc and bioenergetic value to mudworm on ingestion rate from effect on bioavailability before inferring influence of foc or other factors on MeHg bioavailability from correlations.
- This conclusion should be generalizable to all ration, sediment, or soil contaminants, with the proviso that foc and bioenergetic values must be parsed by size fraction for particle size-sorting benthic macroinvertebrates.

Recommendations

- When mudworm bioassay results are to be used to evaluate influence of sediment or soil parameters on contaminant bioaccumulation or bioavailability, method should be modified to require measurement of test sediment or soil ingestion rate and organic carbon assimilation efficiency by measuring the difference between ingested medium and feces TOC.

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