

A Study of Multiphase Flow in CO₂-EOR: Impacts of Three-Phase Relative Permeability and Hysteresis Models*

Wei Jia¹, Brian McPherson¹, Feng Pan², Zhenxue Dai³, Nathan Moodie¹, and Ting Xiao¹

Search and Discovery Article #80669 (2019)**

Posted February 25, 2019

*Adapted from oral presentation given at 2018 AAPG Annual Convention & Exhibition, Salt Lake City, Utah, May 20-23, 2018

**Datapages © 2019 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/80669Jia2019

¹Department of Civil & Environmental Engineering, University of Utah, Salt Lake City, Utah, United States (wei.jia@utah.edu)

²Utah Division of Water Resources, Salt Lake City, Utah, United States

³Jilin University, Changchun, China

Abstract

Multiphase flow in geological CO₂ sequestration (GCS) is fundamental to CO₂ migration and storage. Due to the presence of the oil phase (or non-aqueous liquid phase), GCS with enhanced oil recovery (CO₂-EOR) includes complex multiphase flow processes compared to GCS in deep saline aquifers (no hydrocarbons). Two of the most important factors are relative permeability and associated hysteresis effects, both of which are difficult to measure and are usually represented by empirical interpolation models.

This study aims to quantify the impacts of different three-phase relative permeability models and hysteresis models on CO₂ sequestration simulation results. Investigated options of three-phase relative permeability models include the Stone I and Stone II models, a saturation-based weighted segregated model, and a linear model. Studied hysteresis models include a three-phase water-alternating-gas (WAG) hysteresis model, the Carson model, and the Land model. We chose the SACROC unit, an active CO₂-EOR site located in West Texas, as a case study. Simulation results of forecasted CO₂ storage suggest that (1) the choice of three-phase relative permeability model and hysteresis model have noticeable impacts on CO₂ sequestration simulation results, (2) impacts of three-phase relative permeability models and hysteresis models on CO₂ trapping are sensitive to different stages of simulation period, i.e., during and after CO₂ injection, and (3) the specific choice of hysteresis model is more important relative to the choice of three-phase relative permeability model.

References Cited

Han, W.S., 2008, Evaluation of CO₂ Trapping Mechanisms at the SACROC Northern Platform: Site of 35 years of CO₂ Injection: PhD Dissertation, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Juanes, R., J. Spiteri, F.M. Orr Jr., M.J. Blunt, 2006, Impact of relative permeability hysteresis on geological CO₂ storage: Water Resources Research, v. 42, W12418. doi:10.1029/2005WR004806

Oak, M.J., 1991, Three-phase relative permeability of intermediate-wet Berea sandstone: SPE-22599-MS, presented at SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Dallas, Texas, Oct. 6-9



AAPG

A Study of Multiphase Flow in CO₂-EOR: Impacts of Three-Phase Relative Permeability and Hysteresis Models

Wei Jia*, Brian McPherson, Feng Pan, Zhenxue Dai, Nathan Moodie, Ting Xiao

University of Utah

May 21, 2018



ACE 101: Bridging Fundamentals and Innovation

DISCLAIMER

- This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ACKNOWLEDGEMENTS

Funding for this project is provided by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL through the Southwest Regional Partnership on Carbon Sequestration (SWP) under Award No. DE-FC26-05NT42591.



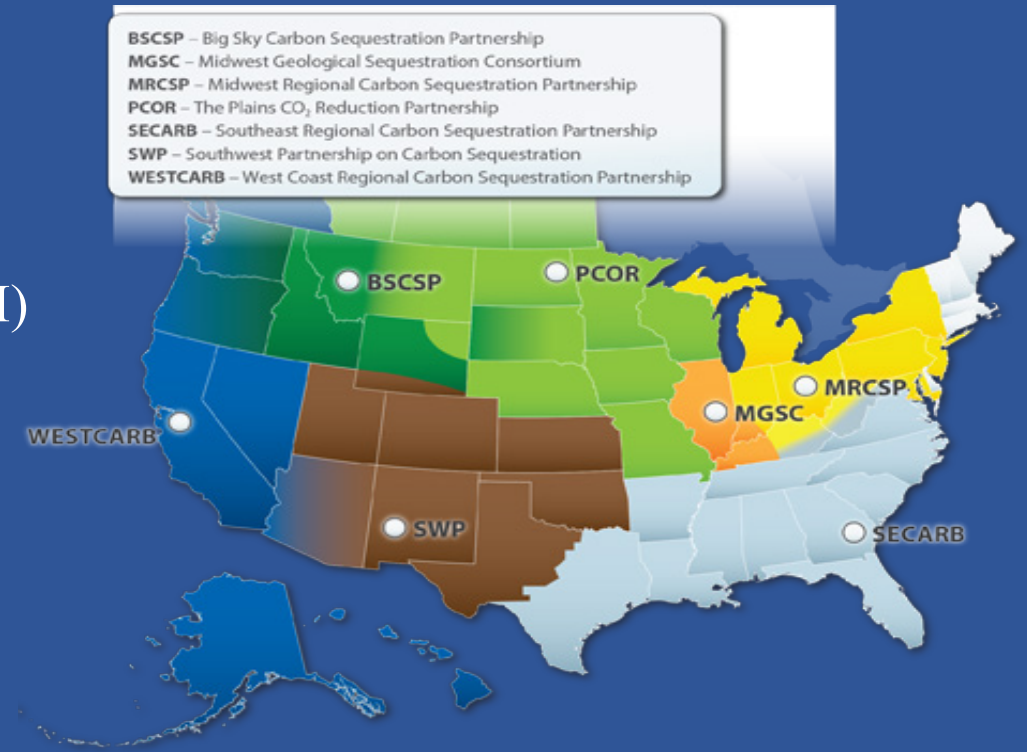
OUTLINE

- Introduction
 - Three-Phase Relative Permeability Models
 - Hysteresis Models
 - Research Goals
- Case Study
 - Methods
 - Results
- Summary

INTRODUCTION

Southwest Regional Partnership (SWP)

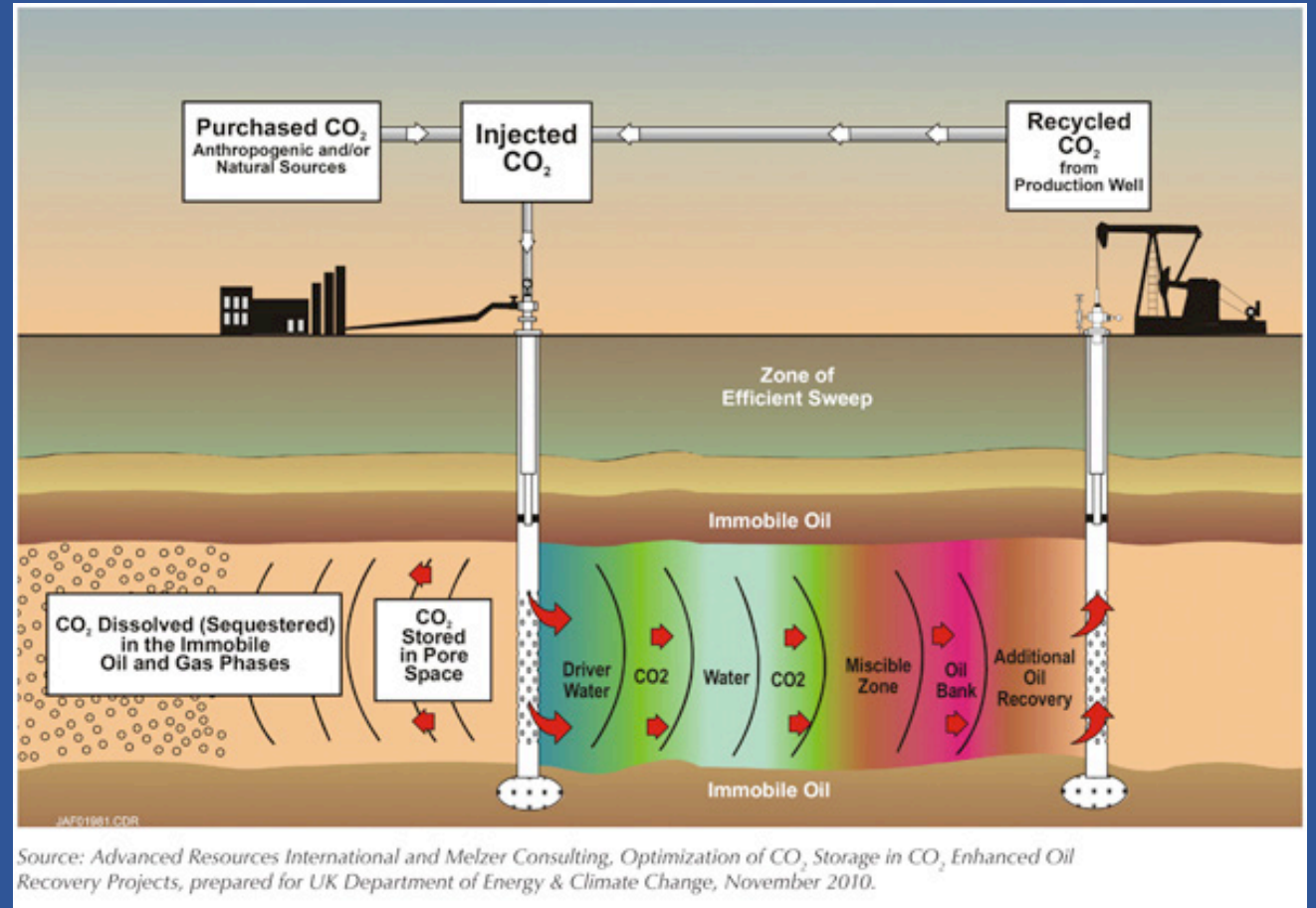
- CO₂-EOR:
 - SACROC, Permian Basin, Texas (Phase II),
 - Aneth, Paradox Basin, Utah (Phase II),
 - Farnsworth Unit, Anadarko Basin, Texas (Phase III)
- CO₂-ECBM:
 - San Juan Basin, New Mexico (Phase II)



INTRODUCTION

CO₂-Enhanced Oil Recovery

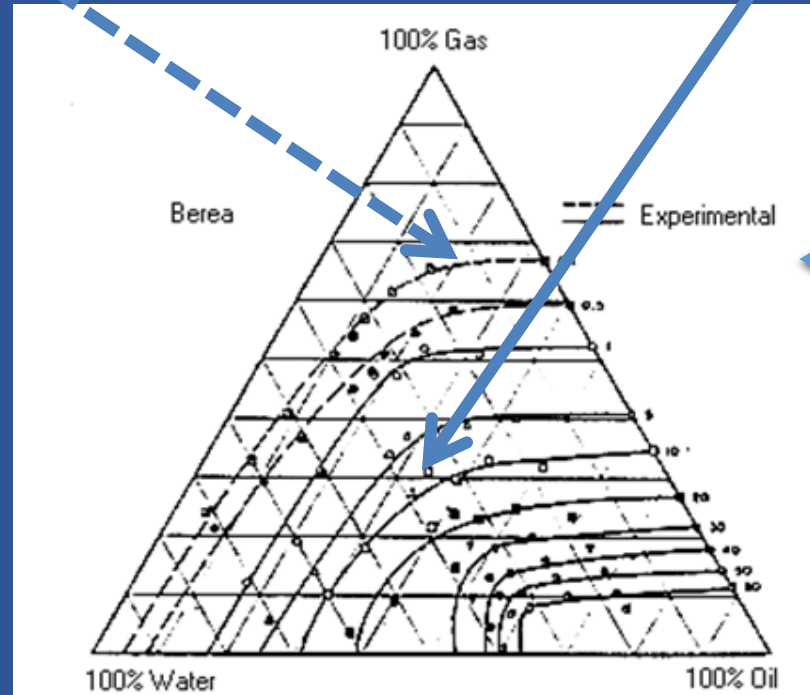
- CO₂ storage
- Three-Phase system (oil/water/CO₂)
- CO₂-WAG injection scheme



THREE-PHASE REL. PERM. MODELS

Experiment data of oil isoperm values

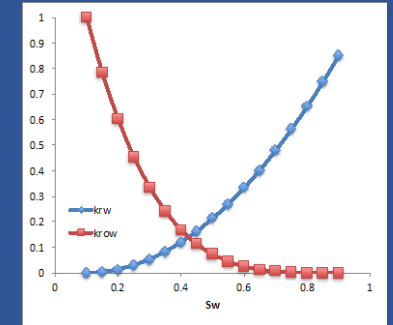
- Expensive
- Time-consuming



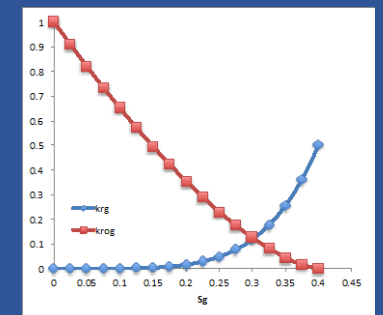
$$k_{ro} = \frac{k_{row}k_{rog}SS_o}{k_{rocw}(1 - SS_w)(1 - SS_g)}$$

3-Phase
Rel. Perm.
Model

Water/Oil



Oil/Gas



(source: Oak et al., 1991)

THREE-PHASE REL. PERM. MODELS

Commonly used models:

- Stone I model (Rst1)
- Stone II model (Rst2)
- Saturated-weighted model (Rseg)
- Linear isoperm model (Rlin)

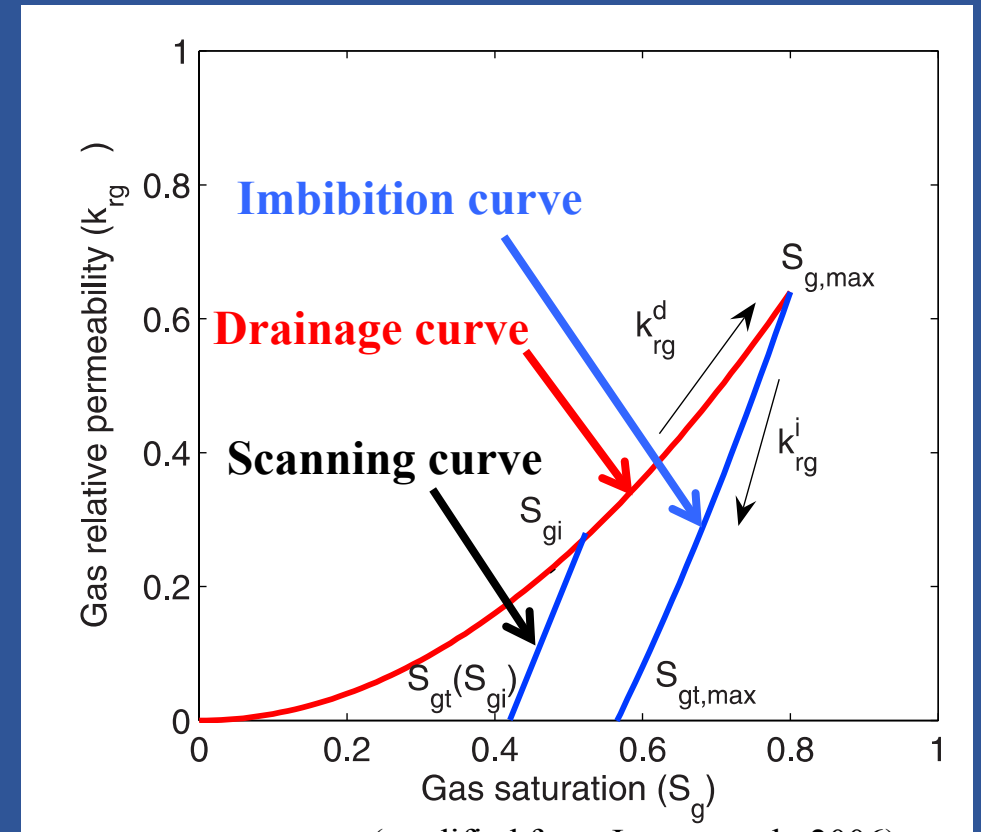
$$k_{ro} = \frac{k_{row}k_{rog}SS_o}{k_{rocw}(1 - SS_w)(1 - SS_g)}$$

$$k_{ro} = k_{rocw}[(\frac{k_{row}}{k_{rocw}} + k_{rw})(\frac{k_{rog}}{k_{rocw}} + k_{rg}) - k_{rw} - k_{rg}]$$

$$k_{ro} = \frac{(S_w - S_{wco})k_{row} + S_g k_{rog}}{S_w + S_g - S_{wco}}$$

HYSTERESIS MODELS

- It is critical to consider hysteresis effect in CO₂ simulations
- Hysteresis effect depends on saturation history
- Hysteresis model calculates k_{rg} and s_{rg} for scanning curve



(modified from Juanes et al., 2006)

HYSTERESIS MODELS

Commonly used models:

- Three-phase WAG hysteresis model (Hwag)

$$k_{rg}(S_g) = k_{rg}^{drain}(S_{gf})$$

$$k_{rg}^{drain} = [k_{rg}^{input} - k_{rg}^{input}(S_g^{start})][\frac{S_{wco}}{S_w^{start}}]^\alpha + [k_{rg}^{imb}(S_g^{start})]$$

- Carlson and Land model (Hcarl)

Generates a scanning curve that is parallel to the imbibition curve

- Land model (Hland)

$$S_{gt} = S_{gc} + \frac{S_{g,hy} - S_{gc}}{1 + C(S_{g,hy} - S_{gc})}$$

$$k_{rg} = S_{gf}^2 [1 - (1 - S_{gf})^{\varepsilon-2}]$$

RESEARCH GOALS

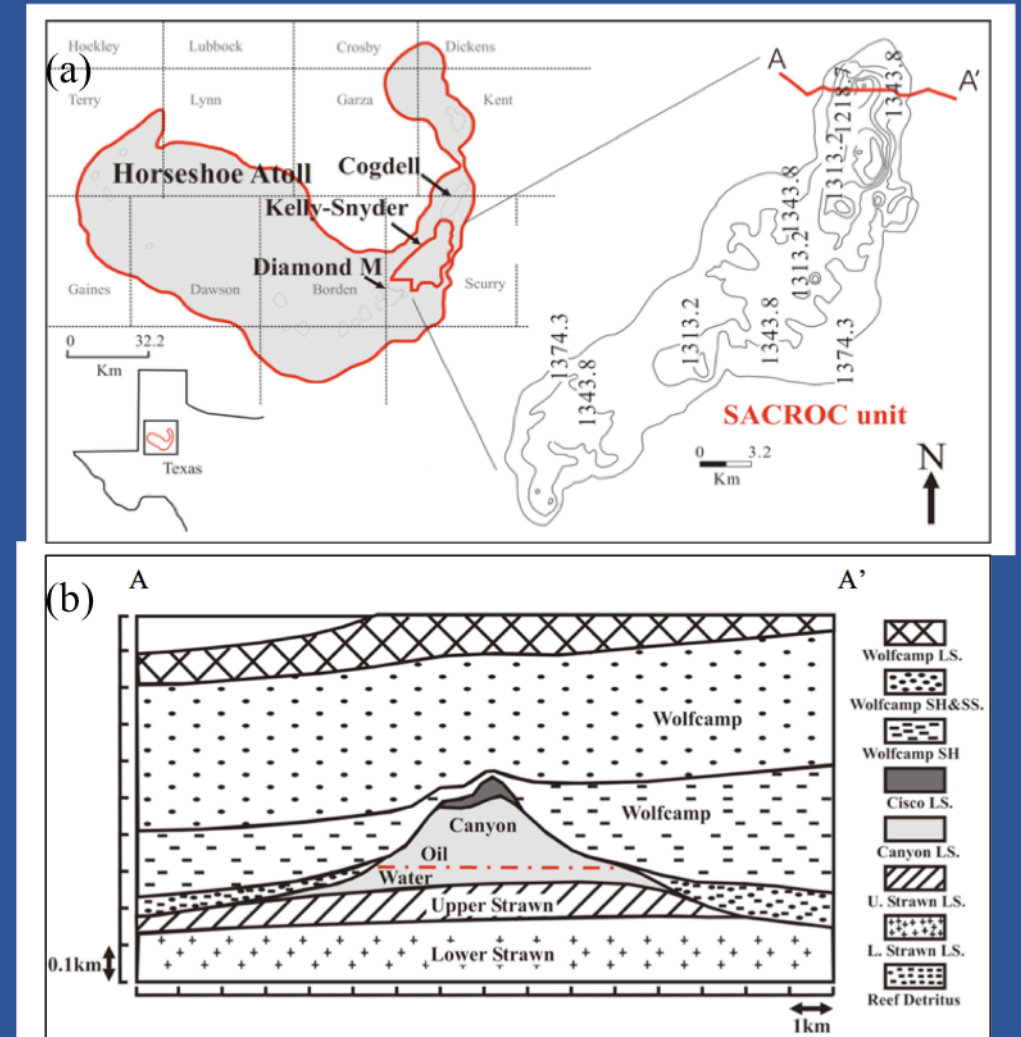
To evaluate impacts of

- Three-phase relative permeability models
- Hysteresis models

on predictions of CO₂ storage in CO₂-EOR

CASE STUDY

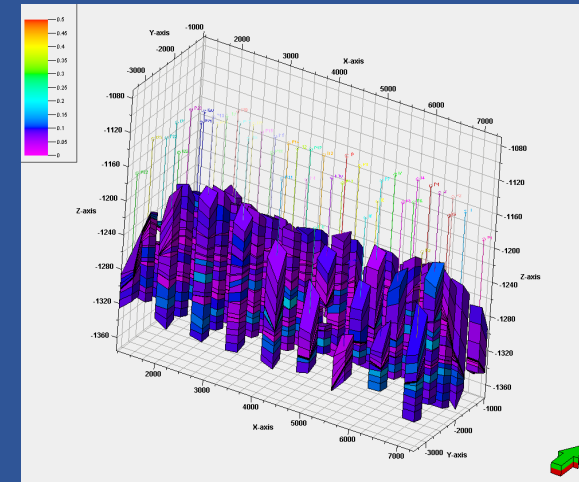
- SACROC unit, western Texas
- CO₂-EOR since 1970s
- 8283m × 3908m × 239m
- 34×16×25=13600 cells
- Constant pressure B.C. at southern boundary
- 16.45 MPa as I.C. for CO₂-EOR



(modified from Han, 2007)

CASE STUDY

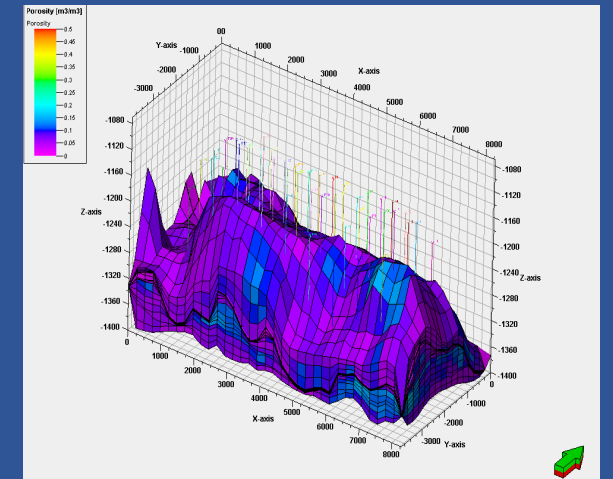
- 23 prod. wells, 22 inj. wells
- 30 yrs. of CO₂-EOR + 20 yrs. of post-EOR CO₂ inj.(no prod.) + 50 yrs. of monitoring (no inj.)
- 50 heterogeneous realizations of porosity and permeability (to minimize impact of deterministic property distribution)
- Simulator: CMG-GEM



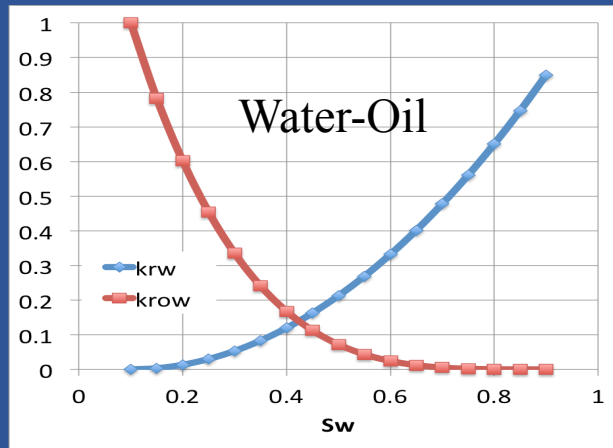
Synthetic well logs

Sequential Gaussian Simulation

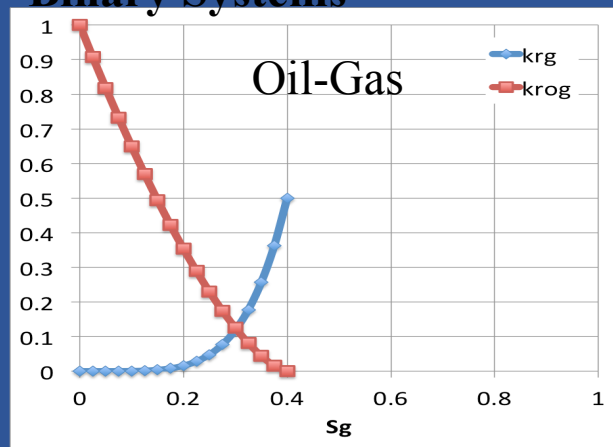
One of 50 possible realizations



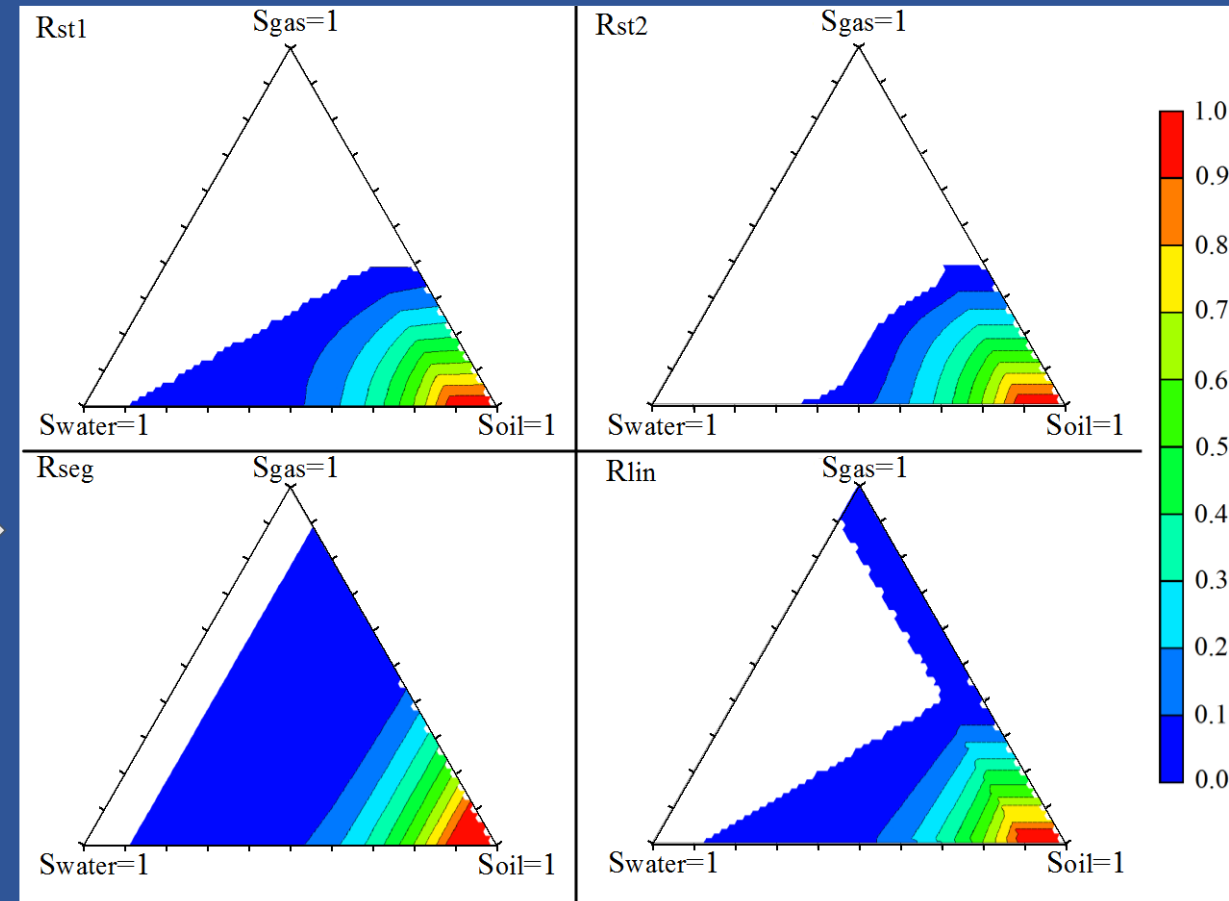
METHODS



Experiment Data From
Binary Systems



k_{ro} interpolation
models

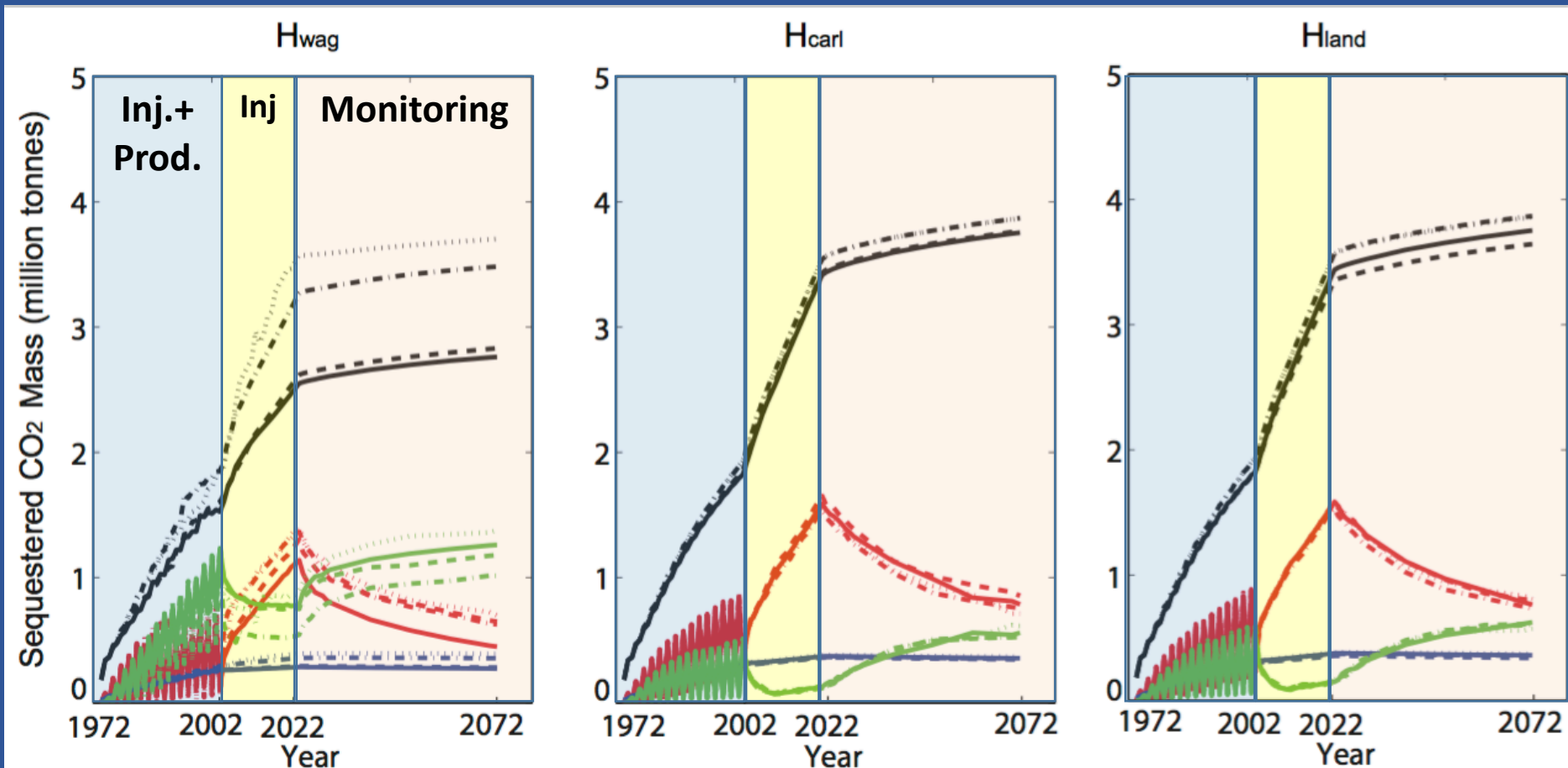


METHODS



RESULTS

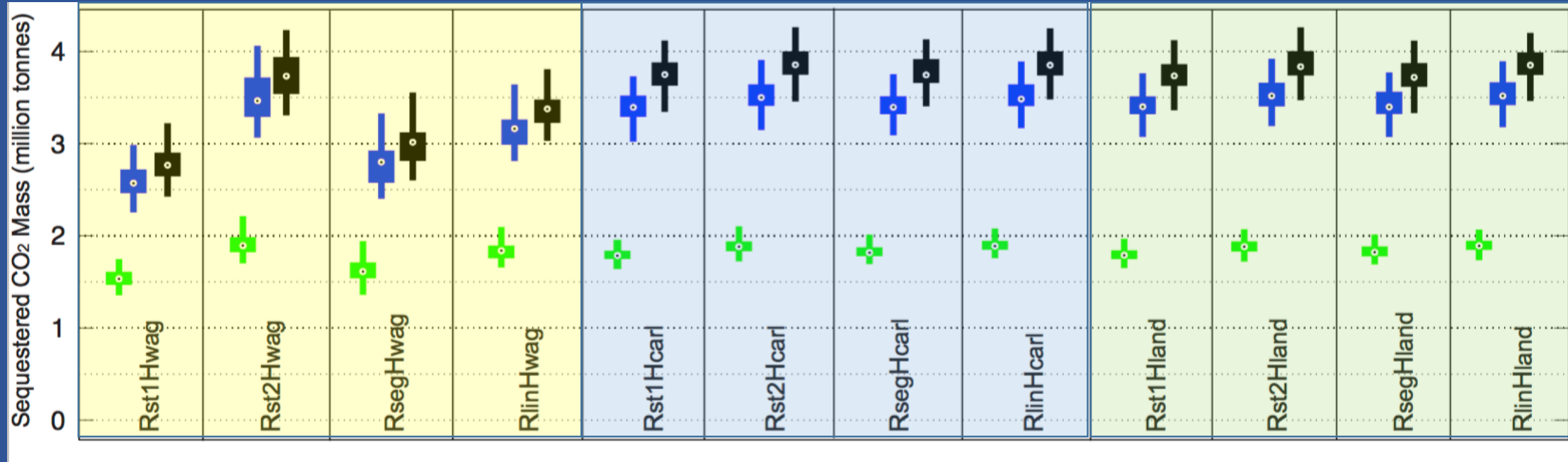
Mass of Sequestered CO₂ Using Different Hysteresis Models



Black: CO₂ dissolved in oil phase;
Red: CO₂ in free supercritical phase;
Green: CO₂ in residually trapped supercritical phase;
Blue: CO₂ dissolved in aqueous phase.
Solid line: Rst1
Dash-Dot: Rst2
Dashed: Rseg
Dotted: Rlin

One of 50 possible realizations

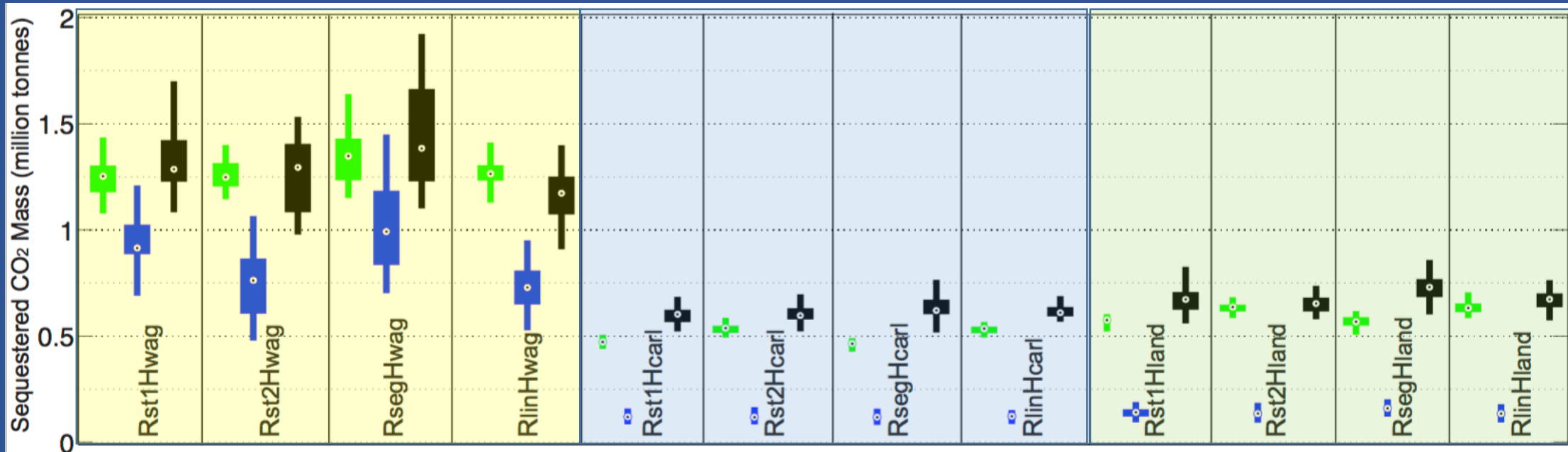
CO₂ in Oil Phase



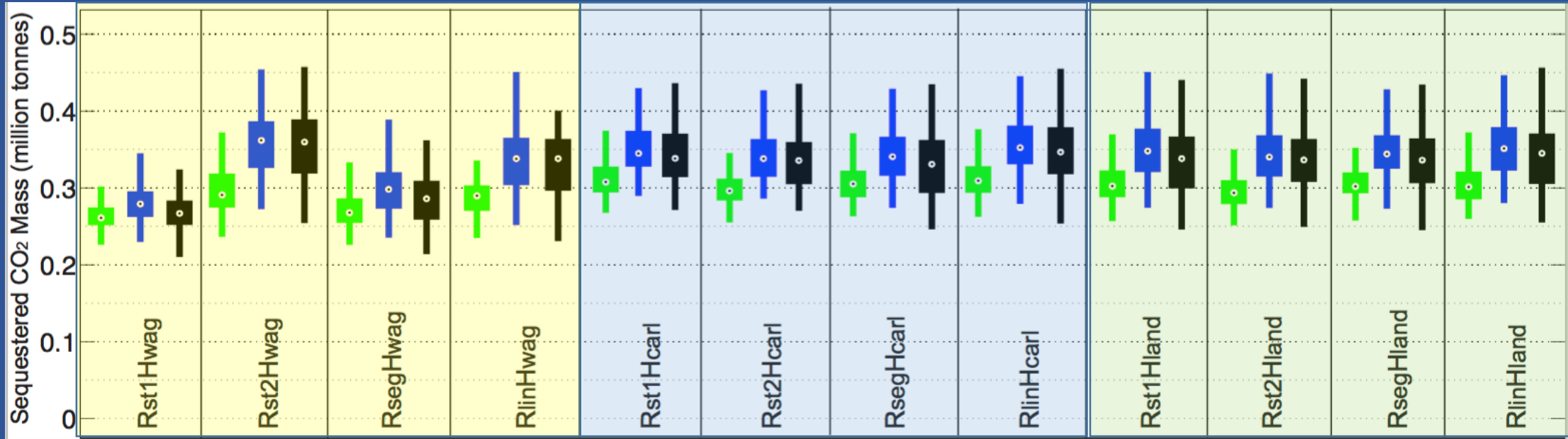
CO₂ in Free Supercritical Phase



CO₂ in Residually Trapped Supercritical Phase



CO₂ in Aqueous Phase



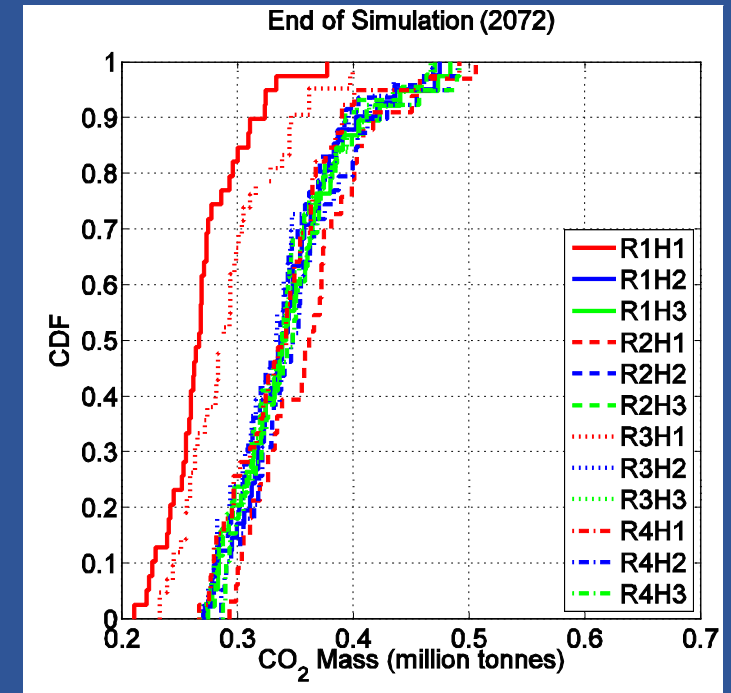
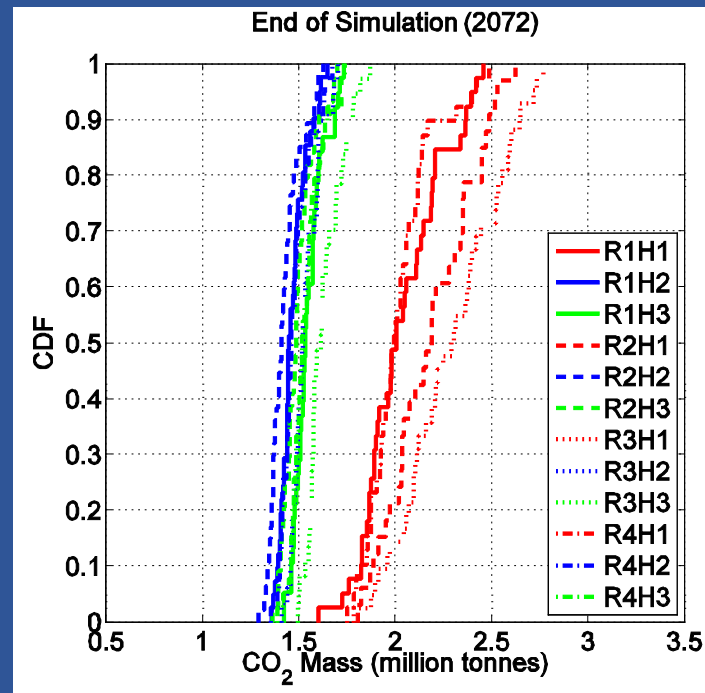
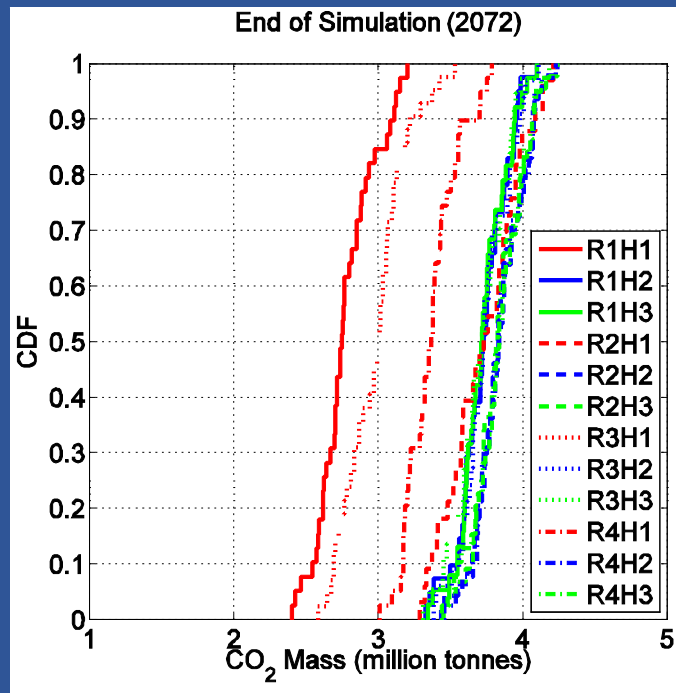
CDFs of CO₂ Storage in Each Phase

Oil: $H_{\text{wag}} < H_{\text{carb}}, H_{\text{land}}$ Supercritical: $H_{\text{wag}} > H_{\text{carb}}, H_{\text{land}}$ Aqueous: $H_{\text{wag}} < H_{\text{carb}}, H_{\text{land}}$

$$R_{\text{st1}} < R_{\text{seg}} < R_{\text{lin}} < R_{\text{st2}}$$

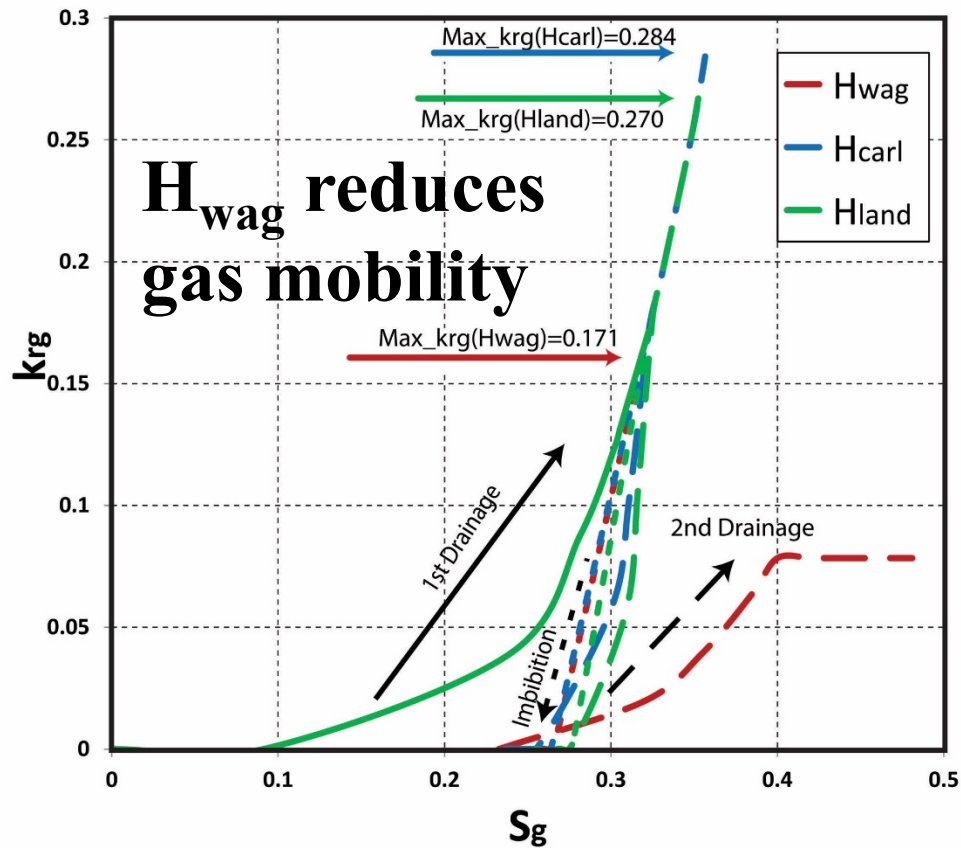
$$R_{\text{lin}} < R_{\text{st1}} < R_{\text{st2}} < R_{\text{seg}}$$

$$R_{\text{st1}} < R_{\text{seg}} < R_{\text{lin}} < R_{\text{st2}}$$

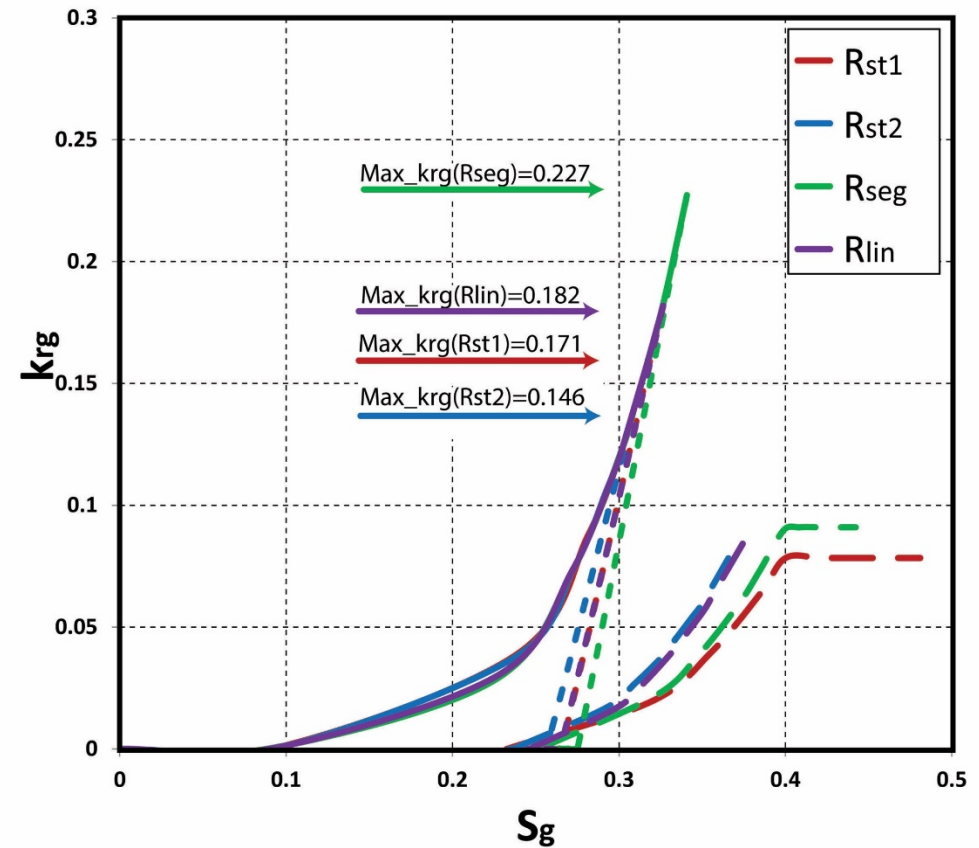


Drainage-Imbibition-Drainage (DID) Test

(a) Impacts of hysteresis models



(b) Impacts of three-phase relative permeability models



SUMMARY

- The choice of three-phase relative permeability model and hysteresis model critically impacts CO₂ sequestration simulation forecasts
- The specific choice of hysteresis model appears to be somewhat more important relative to the choice of three-phase relative permeability model
- Three-phase WAG hysteresis model always predicts lower CO₂ storage in oil and aqueous phase and higher in supercritical phase
- Choice of three-phase relative permeability model has the same impact on predictions of CO₂ in oil and aqueous phase

FUTURE WORK

- Evaluate impacts on oil recovery
- Calibrate with site measurements/reference model
- Integrate with parameter uncertainty
- ...

RESULTS & DISCUSSION

Reference Models:

R2, H3

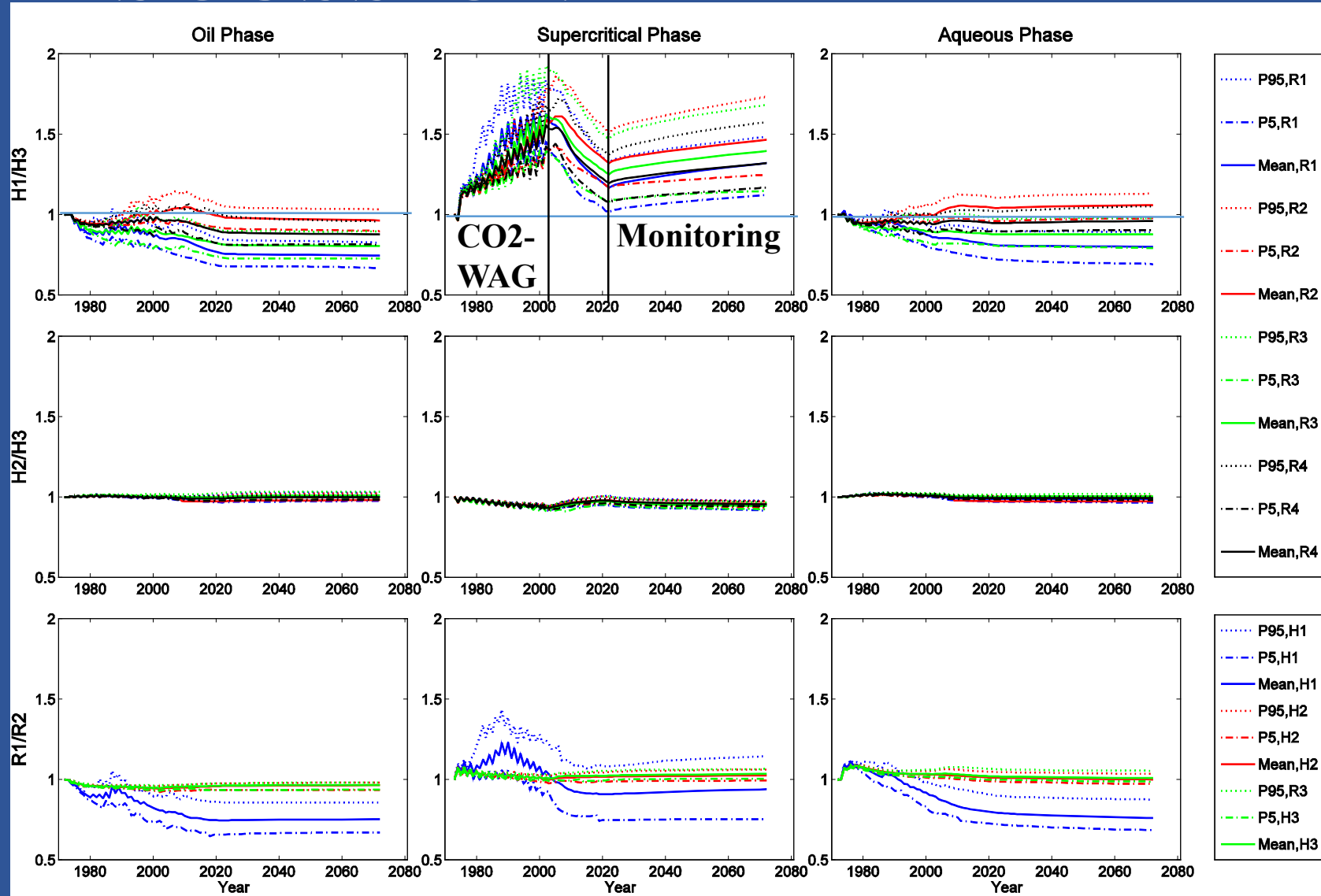
(Default options in CMG-GEM)

Quantify impacts by ratios:

$$\frac{R_j}{R_2}(c_k, t)_{o,g,w} = \frac{\text{Mass}_{\text{CO}_2(o,g,w)}(H_i, R_j, c_k, t)}{\text{Mass}_{\text{CO}_2(o,g,w)}(H_i, R_2, c_k, t)}$$

$$\frac{H_i}{H_3}(c_k, t)_{o,g,w} = \frac{\text{Mass}_{\text{CO}_2(o,g,w)}(H_i, R_j, c_k, t)}{\text{Mass}_{\text{CO}_2(o,g,w)}(H_3, R_j, c_k, t)},$$

$$i=1\sim3, j=1\sim4, c=1\sim50$$

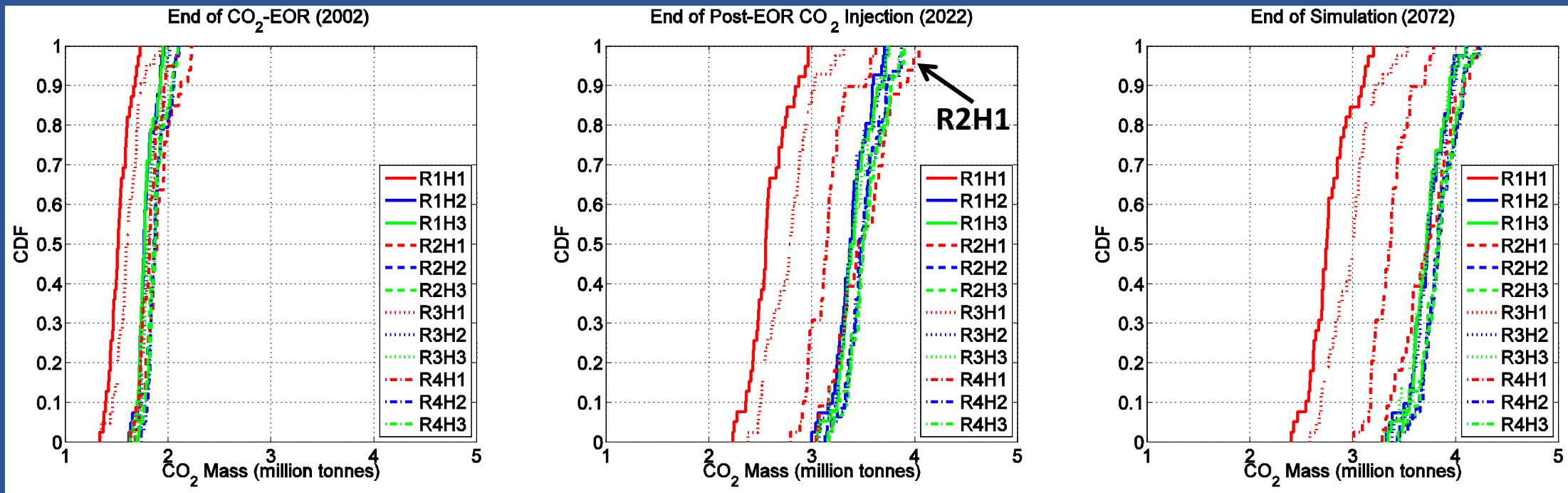


RESULTS & DISCUSSION

CO₂ storage in oil phase:

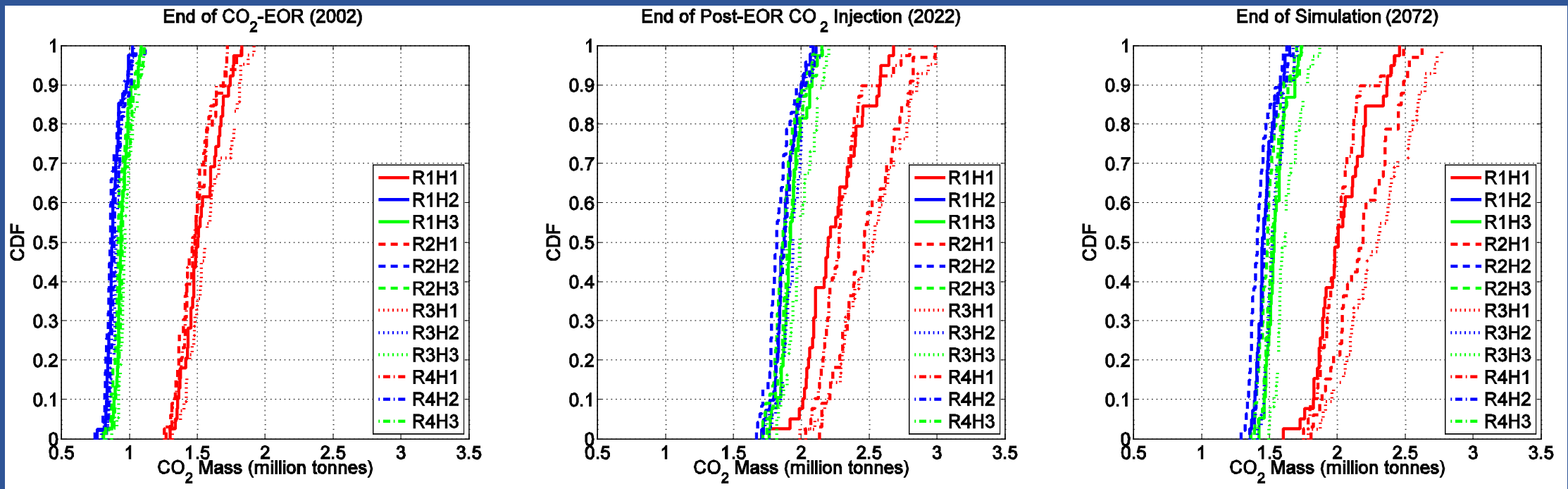
H1<H2,H3

R1<R3<R4<R2



RESULTS & DISCUSSION

CO₂ storage in supercritical phase: $H1 > H2, H3$ $R4 < R1 < R2 < R3$



RESULTS & DISCUSSION

CO₂ storage in aqueous phase: $H1 < H2, H3$

$R1 < R3 < R4 < R2$

