Modeling Complex Problems with System Dynamics: Applications in Animal Agriculture

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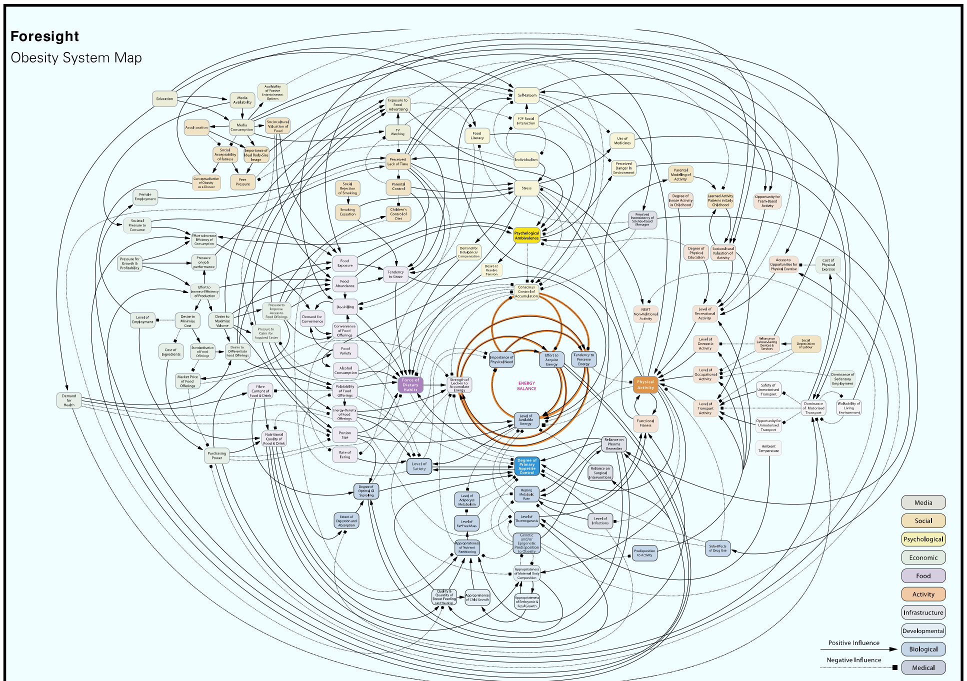
ASAS-ASN Symposium: Future of Data Analytics in Nutrition: Knowledge Gaps, Data Collection and Quality, and the Role of Supporting Tools for Sustainable Development

Cornell CALS
College of Agriculture and Life Sciences

·UEMS·
Universidade Estadual de Mato Grosso do Sul



https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296290/obesity-map-full-hi-res.pdf

"**Complex** interconnections *pose challenges for design of effective policy and scientific study* using many standard tools."

Ross and Dube (2012) "A systems science perspective and transdisciplinary models for food and nutrition security." PNAS.

"To date, most studies that address changes within the food system have taken a *relatively narrow approach with limited consideration of the system's* ***complexity***. However, such approaches can often miss important interconnections and may not capture the full set of impacts flowing from any particular change in the food system."

Nesheim et al. (2015). *A Framework for Assessing Effects of the Food System*. National Academies Press.

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How to Address Complexity?

"**System Dynamics**, Agent-based Models and other computational system science approaches could *complement…[existing]* epidemiological, environmental and macroeconomic *models to better capture the dynamic and adaptive processes*...of these interconnected systems…this is *essential to accelerate understanding*…"

Ross and Dube (2012) "A systems science perspective and transdisciplinary models for food and nutrition security." PNAS.

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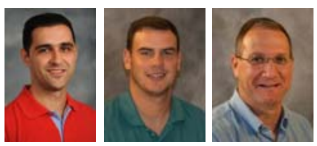
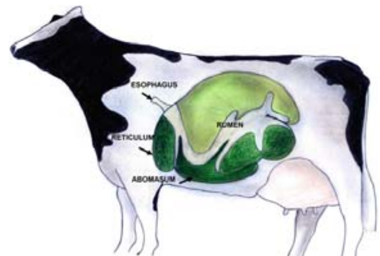
Overview

- What is System Dynamics?
- 2 SD Examples for Animal Agriculture
- SD in graduate training & publishing





Membrive, C.M.B. (2016)

https://agmodelsystems.com

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System Dynamics

- The application of systems engineering concepts to social and economic systems
  - Can include biological systems also
- Simulation modeling based on
  - Systems of ordinary differential equations
  - Solved by numerical integration
- *Applicable to study the origins of dynamic behaviors (and their improvement)*

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SD in Broader View

"A method to enhance learning in complex systems…fundamentally interdisciplinary…grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering…[applied] to solve real-world problems."

– John Sterman, MIT

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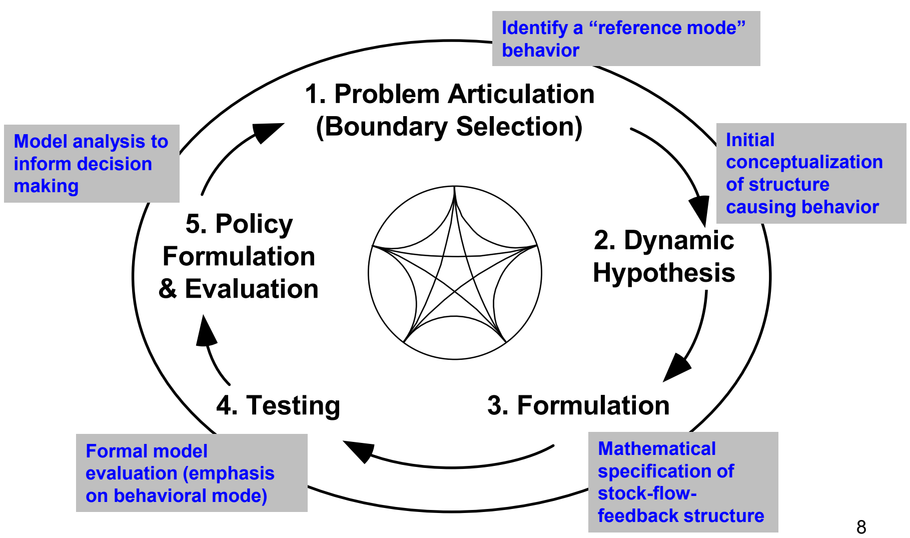
SD Modeling Process



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Adapted from Sterman (2000).

SD Fundamental Idea #1

- System structure causes dynamic behavior
- If we observe a behavior, we can infer something about the underlying structure
- Despite the complexity of behaviors in the world, there are relatively few basic dynamic behavior patterns

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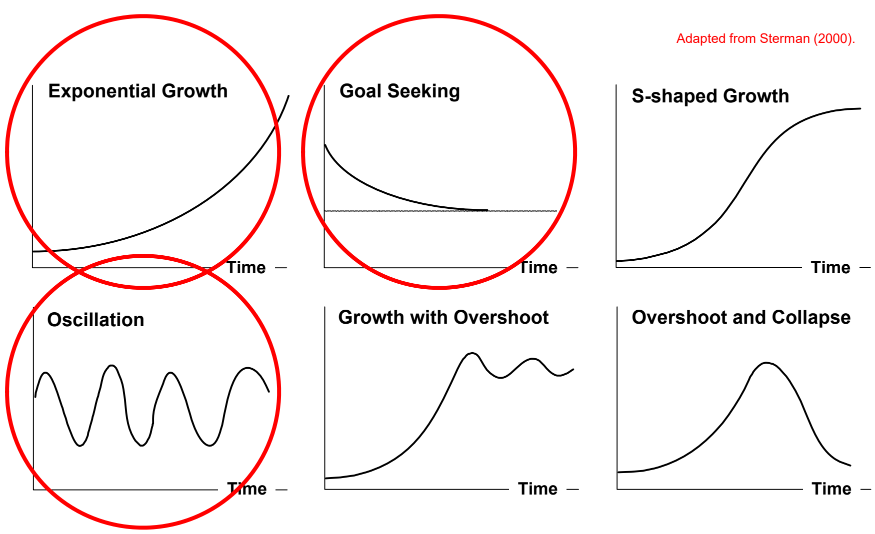
Common Modes of Behavior

Adapted from Sterman (2000).



Three behaviors are basic; others can be viewed as combinations of these

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SD Fundamental Idea #2

- Focus on dynamic complexity
  - Short-run and long-run effects differ due to feedback, delays, nonlinearities
- Simple dynamic systems can generate complex behaviors (e.g., chaos)

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SD Fundamental Idea #3

- Endogenous perspective
  - Behaviors arise from within the system, not just due to external (exogenous) shocks
- “Structure causes behavior”
  - (Problem) behaviors arise from internal system structure
  - Responding requires modifying system structure

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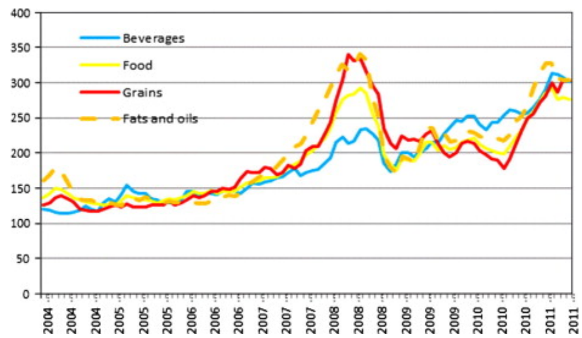
SD Fundamental Idea #3

- Why can't a system respond adequately to shocks?
  - Not "the shock explains the behavior"



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Getaw Tedesse et al (2014)

SD Fundamental Idea #4

- Emphasis on feedback processes
  - Not linear, event-oriented thinking
  - "Situation-decision-action-situation" decision process is assumed
- Positive and negative feedback loops generate many behaviors

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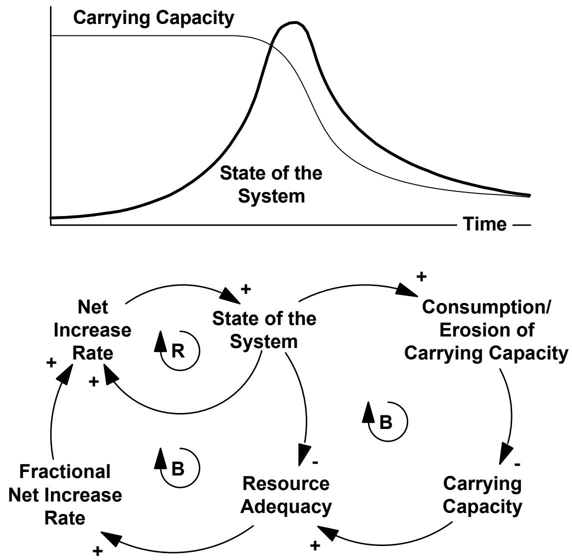
Feedback Structure for "Overshoot and Collapse" Behavior



Adapted from Sterman (2000).

SD Fundamental Idea #5

- Explicit delineation of stocks and flows
- Stocks (states) are accumulations
  - Material or information
- "State-rate" structure
  - Rates affect states, states affect rates

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SD Fundamental Idea #5

Field	Stocks	Flows
Mathematics, physics and engineering	Integrals, states, state variables, stocks	Derivatives, rates of change, flows
Chemistry	Reactants and reaction products	Reaction rates
Manufacturing	Buffers, inventories	Throughput
Economics	Levels	Rates
Accounting	Stocks, balance sheet items	Flows, cash flow or income statement items
Biology, physiology	Compartments	Diffusion rates, flows
Medicine, epidemiology	Prevalence, reservoirs	Incidence, infection, morbidity and mortality rates

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SD Fundamental Idea #6

- Broader variable and data definitions
  - Use of information from personal experience and unpublished records
  - Use of "soft" and conceptual variables
- Build a model based only on existing data?
  - This assumes that omitted variables effect = 0 !
  - Develop a good structure
  - Model can be used to assess data priorities

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Two SD Modeling Process Examples

- Applications to Animal Agriculture
  - At different scales
  - Different disciplinary focus
- Rumen fill dynamics (CNCPS)
- Brazil dairy sector

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CNCPS v.7 Rumen Fill Dynamics Submodel

Cornell University

Search Cornell

Cornell Net Carbohydrate and Protein System

HOME | SOFTWARE | INSTALLATION AND PURCHASE | PUBLICATIONS | CONTRIBUTORS | SUPPORT

The Cornell Net Carbohydrate and Protein System (CNCPS) was developed to predict requirements, feed utilization, animal performance and nutrient excretion for dairy and beef cattle using accumulated knowledge about feed composition, digestion, and metabolism in supplying nutrients to meet requirements.

- Focus on the stock-flow dynamics related to rumen fill for two B3 and C fiber fractions

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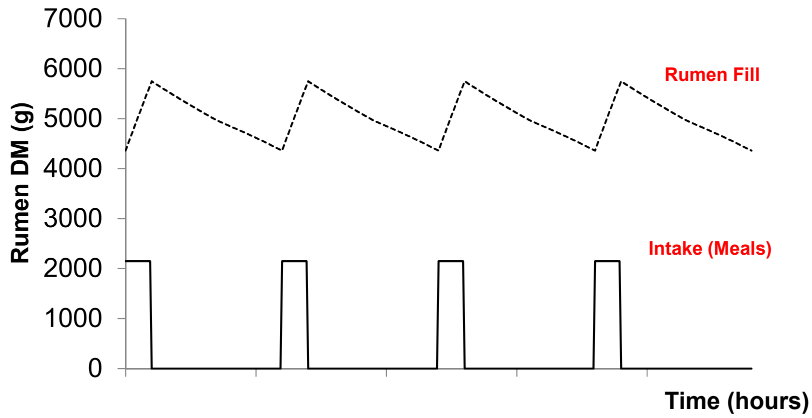
Reference Mode Behavior

(Intake and Rumen DM)



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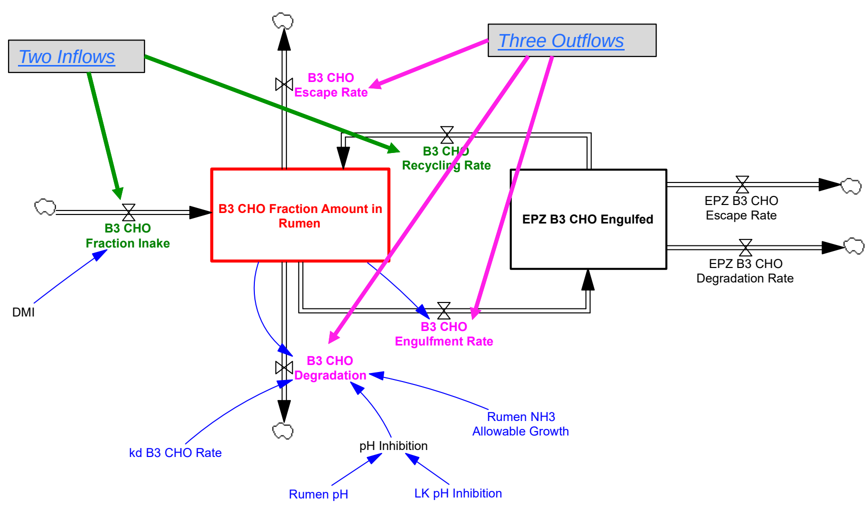
System Structure Diagram

("Dynamic Hypothesis")



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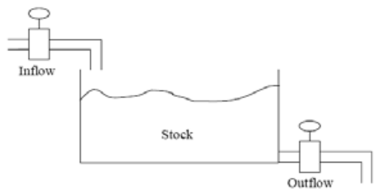
Four equivalent representations of stock and flow structures

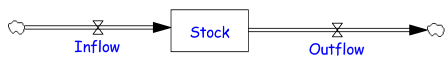
Adapted from Sterman (2000).



Hydraulic metaphor

$$S(t) = \int_{t_0}^{t} [I(s) - O(s)]ds + S(t_0)$$

Integral equation



Stock and flow diagram

$$\frac{dS}{dt} = I(t) - O(t)$$

Differential equation

These all mean the same. (Which to use depends on the audience.)

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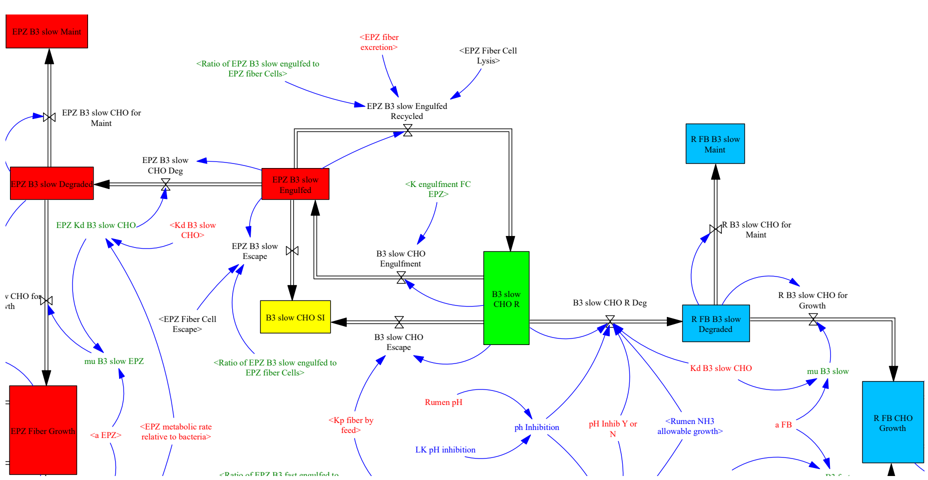
System Model

(Small Part of Stock-Flow Structure)



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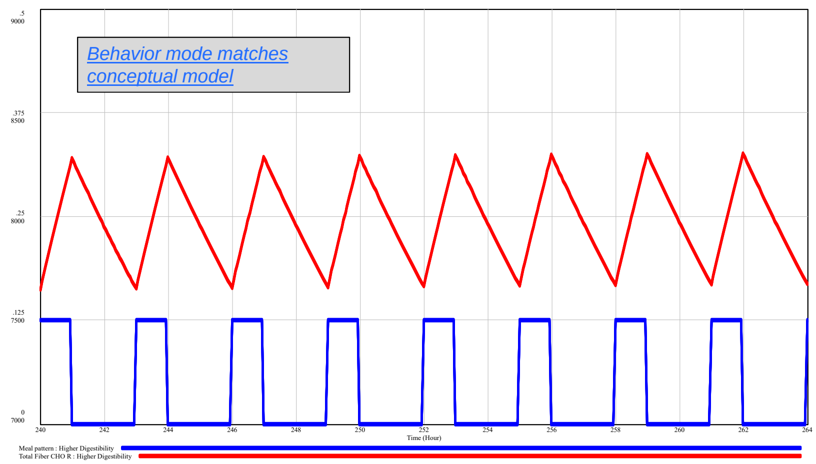
Model Evaluation

(Total Fiber CHO in Rumen)



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Model Analysis: Impact of Improved Digestibility

<u>Scenarios:</u>

- Standard diet – Corn silage 35% DM 37% NDF
- High and Low aNDFom digestibility corn silage variety
  - +/-10% rumen fill
- All must converge to similar rumen fill set point

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Cow-Related Assumptions

- 1,653 lb (750 kg) cow producing 90 lb (41 kg) milk
- Consuming 54 lb (24.5 kg) DMI
  - 32% aNDFom
- 17.28 lb aNDFom intake (7.84 kg)
  - 7,840 g aNDFom intake
  - 1% body weight
  - 2017 Agronomic factors

Animal Inputs	Value
Inputted milk (lb)	90
Energy corrected milk (lb)	94
Milk Fat %	3.7
Milk True Protein %	3.1
Body weight (lb)	1,653
BCS	3.0
Days since calving	110
Age (months)	39

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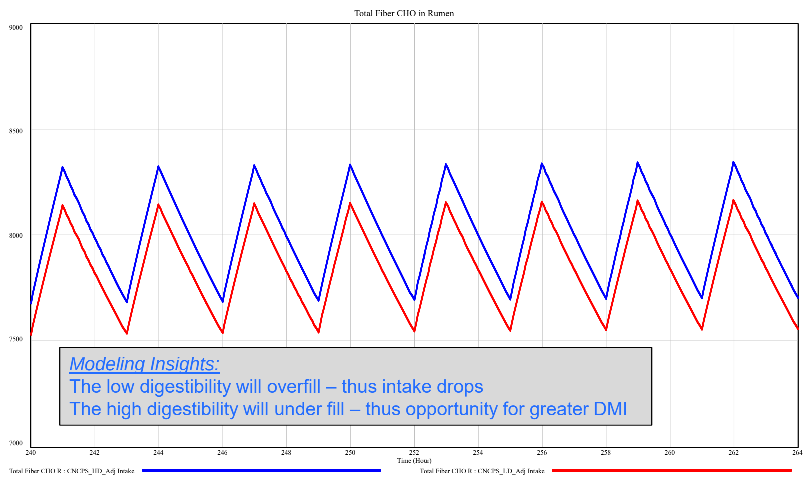
Feed Assumptions for Scenario Analysis

Chemical composition	Low aNDFom digestibility	Base	High aNDFom digestibility
CP (% DM)	7.0	7.5	8.1
aNDFom (% DM)	37.7	37.3	37.8
Starch (% DM)	36.0	37.1	32.1
uNDFom30 (% aNDFom)	47.8	45.1	41.4
uNDFom120 (% aNDFom)	38.6	34.7	29.8
uNDFom240 (% aNDFom)	36.7	32.6	27.7
Fast pool aNDFom (% aNDFom)	49.5	51.8	55.4
Slow pool aNDFom (% aNDFom)	13.0	15.0	16.0
uNDFom pool (% aNDFom)	36.7	32.6	27.7
Fast kd (%/h)	12.4	12.1	11.6
Slow kd (%/h)	1.8	1.8	1.8
Integrated kd (%/h)	6.3	5.9	5.9

Model Analysis
(Total Fiber CHO in Rumen)



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Brazil Dairy Sector Model

- <u>Objective:</u> Analyze the potential impact of use of technologies to enhance cow productivity on market dynamics
  - Improved genetics and <u>nutritional management</u>
- Outcomes of interest:
  - Milk production and price
  - Farm profitability
  - Welfare of farms by type

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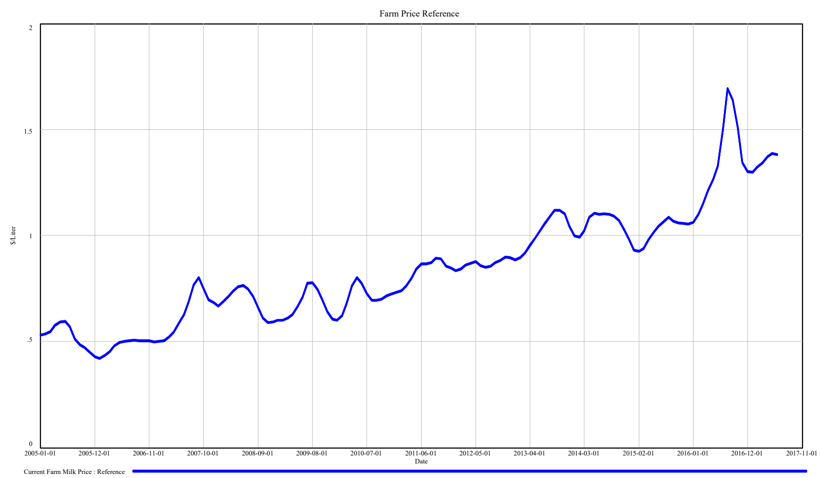
Reference Mode Behavior

(Average Farm Milk Price)



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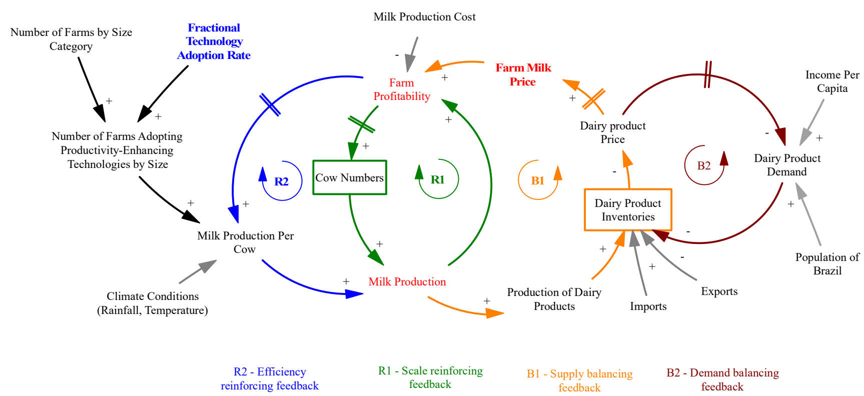
Adapted from Simões (2018)

System Structure Diagram

("Dynamic Hypothesis")



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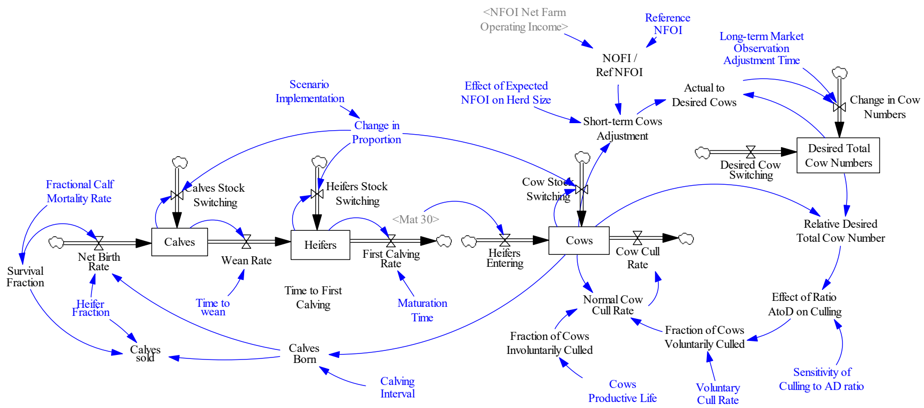
Adapted from Simões (2018)

System Model

(Herd Aging Chain Component)



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Adapted from Simões (2018)

System Model

(Herd Aging Chain Component)

Actual to Desired Cows[S,T]
= Short term Cows Adjustment[S,T] - Desired Total Cow Numbers[S,T]

Calves[S,T]
= INTEG (Net Birth Rate[S,T] +Calves Stock Switching[S,T]-Wean Rate[S,T], Initial Heifer Stock[S,T]*(Time to wean[S,T]/Time to First Calving[S,T]))

Calves Born[S,T]
= Cows[S,T]/Calving Interval[S,T]

Calves Sold[S,T]
= Calves Born[S,T]*(1-Heifer Fraction[S,T])*Survival Fraction[S,T]

Cow Cull Rate[S,T]
= Normal Cow Cull Rate[S,T]

Cows[S,T]
= INTEG (Cow Stock Switching[S,T]+Heifers Entering[S,T]-Cow Cull Rate[S,T], Initial Milk Cows[S,T]*Initial Fraction of Cows in Each Category[S,T])

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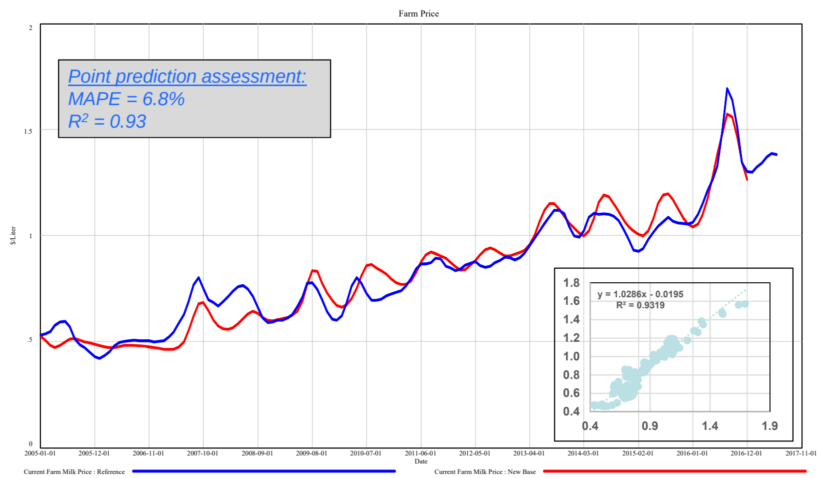
Adapted from Simões (2018)

Model Evaluation

(Milk Price Behavioral Mode)



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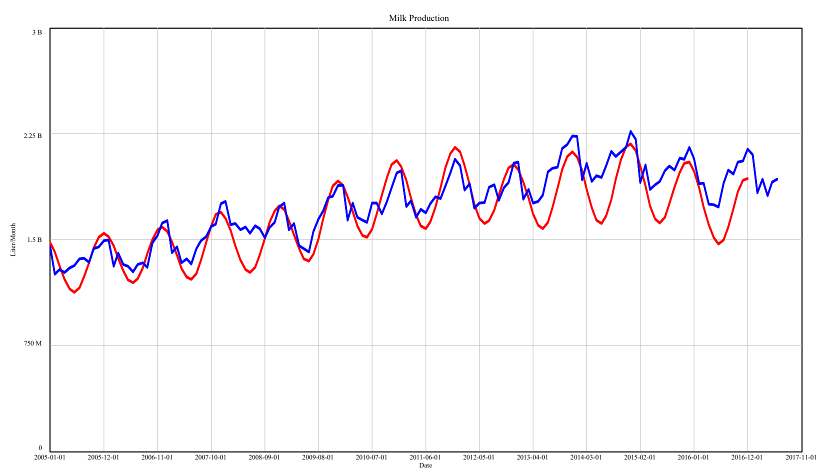
Adapted from Simões (2018)

Model Evaluation

(Milk Production Behavioral Mode)



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Adapted from Simões (2018)

Model Evaluation

(Other Tests)

- Family Member
- Structure Assessment
- Integration Error
- Dimensional Consistency
- Parameter Assessment
- Behavior anomaly
- Sensitivity Analysis
- System Improvement
- Boundary Adequacy
- Extreme Conditions
- *Feedback loop dominance*

Adapted from Sterman (2000).

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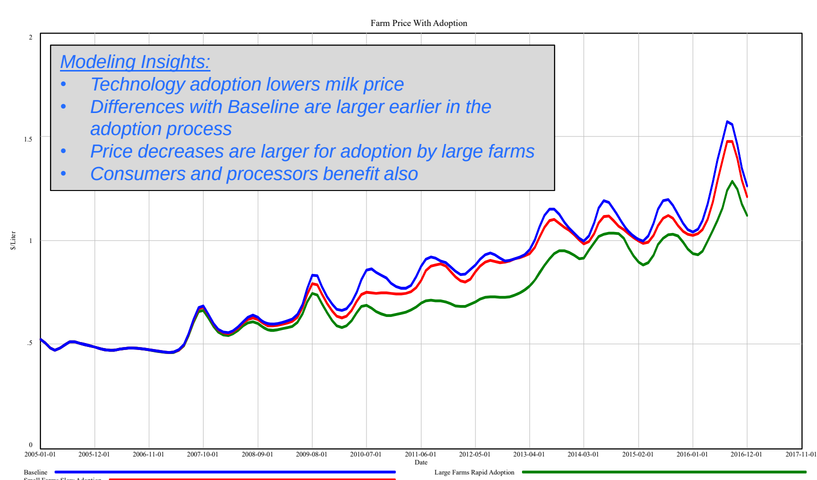
Model Analysis

(Milk Price Impacts)



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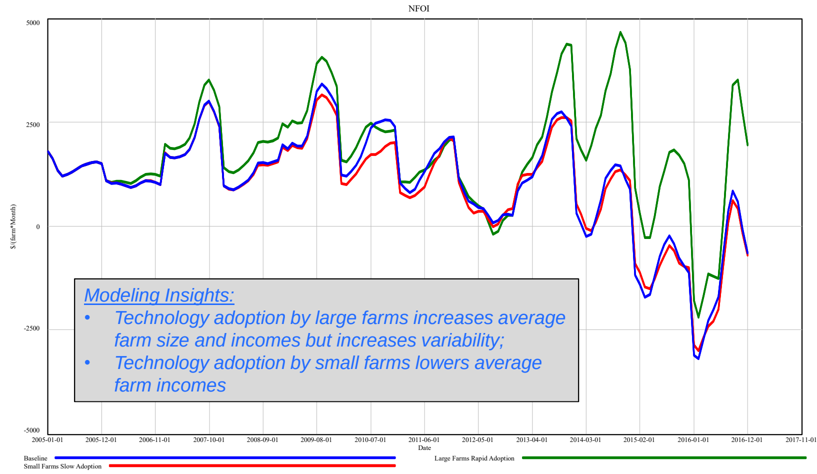
Adapted from Simões (2018)

Model Analysis

(Impacts on Average Farm Income)



Modeling Insights:

- *Technology adoption by large farms increases average farm size and incomes but increases variability;*
- *Technology adoption by small farms lowers average farm incomes*

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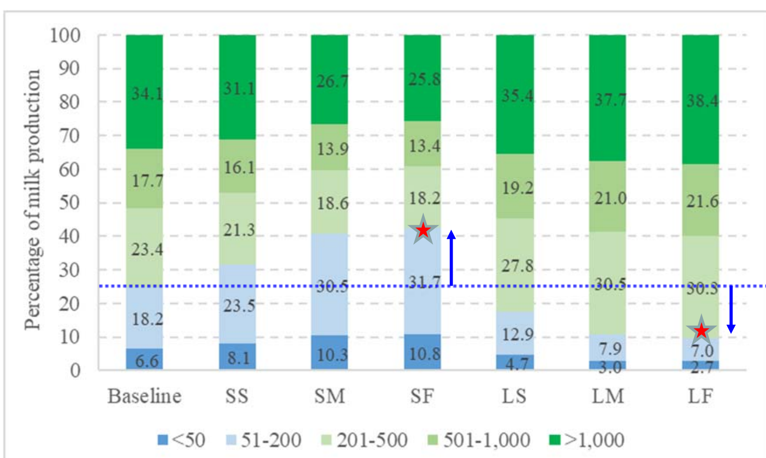
Adapted from Simões (2018)

Model Analysis

(Distribution of Milk Production by Size)



Modeling Insights:

- *Technology adoption can markedly alter the distribution of milk production and farm welfare*

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Adapted from Simões (2018)

SD in Graduate Training?

- As a "Discipline Plus" component
- Example: Cornell *Food Systems and Poverty Reduction* IGERT 2010-2014
- Integrating systems modeling course and interdisciplinary field working groups

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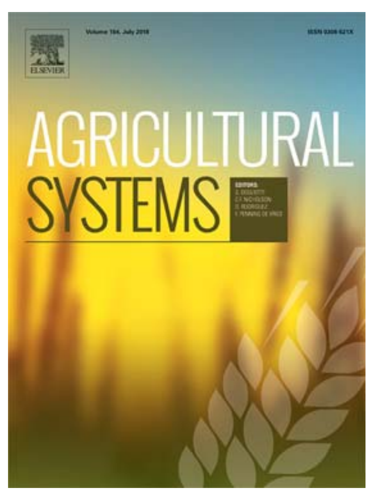
SD & Publishing

- SD based research is publishable
- Work must be of highest quality
  - Method criticized, not implementation
- Journal focus more important?



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Concluding Comments

- Many relevant research questions and problem situations require consideration of (dynamic) complexity
- SD (and other methods) can be useful tools when appropriately applied
- Graduate training in applied biological sciences can usefully include courses in SD and other simulation modeling

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References

Getaw Tadesse, Bernardina Algieri, Matthias Kalkuhl, Joachim von Braun. 2014. Drivers and triggers of international food price spikes and volatility. *Food Policy*, 47:117-128.

Membrive, C.M.B. (2016) Anatomy and Physiology of the Rumen. In: Millen D., De Beni Arrigoni M., Lauritano Pacheco R. (eds) Rumenology. Springer, Cham.

SIMÕES, A. R. P. (2018) The Dynamic Impacts of Farm-Level Technology Adoption on Production, Pries and Profitability in Brazil's Dairy Supply Chain. PhD dissertation, Universidade Federal de Viçosa.

Sterman, J. D. (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill.

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