The NREL BioLUC and Biomass Scenario Models Illustrating a System Dynamics Approach

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CRC LIFE CYCLE ANALYSIS OF TRANSPORTATION FUELS WORKSHOP | 2017-10-26

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Lexidyne Simulation Data Analytics

Acknowledgements and Disclaimers

- Thanks to:
  - US Department of Energy/BETO: Project sponsorship and funding
  - NREL BSM Team (Emily Newes et al)
  - NREL BioLUC team (Danny Inman et al)

- The findings and conclusions of this presentation are those of the author and do not necessarily represent the official position of DOE or NREL

Illustrating a System Dynamics Approach to LCA

OVERVIEW

- Motivation
- A quick look at the system dynamics approach
- BioLUC: Global land use change dynamics
  - What's in the model?
  - Illustrative results
- Biomass Scenario Model: Evolution of the supply chain for biofuels
  - How does it work?
  - A simulation experiment
  - Possible model explorations
- Summary and Discussion

Motivation

and comprehensive economic models. More specifically, the move toward MMMR-PE models and CGE models demonstrates this trend. One early example of a study that used MMMR-PE modeling is Dalgaard et al. (2008). They utilize a Dutch agricultural model to identify marginal rapeseed and spring barley producers among the 31 farm types, so that marginal Danish data and not average data were used. Searchinger et al. (2008) utilized FAPRI to project the affected technologies associated with an increase in demand for corn-based ethanol. More recent efforts, by the US EPA

and Heijungs 2010, Gallego et al. 2010).

Rebound effects and experience curves represent complex economic phenomena that can lead to indirect environmental impacts. We only identified a few studies that examined rebound effects in the context of LCA. Moreover, only one study has investigated the integration of experience curves and LCA. Both of these topics represent opportunities for further research. One field that was not present in the literature reviewed is system dynamics. Future research might work to advance CLCA

by linking to the well-established field of system dynamics, particularly with relevance to causality or consequences reflective of real-world behavior (Halog and Manik 2011).

Ekvall T, Weidema B (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 3:161–171

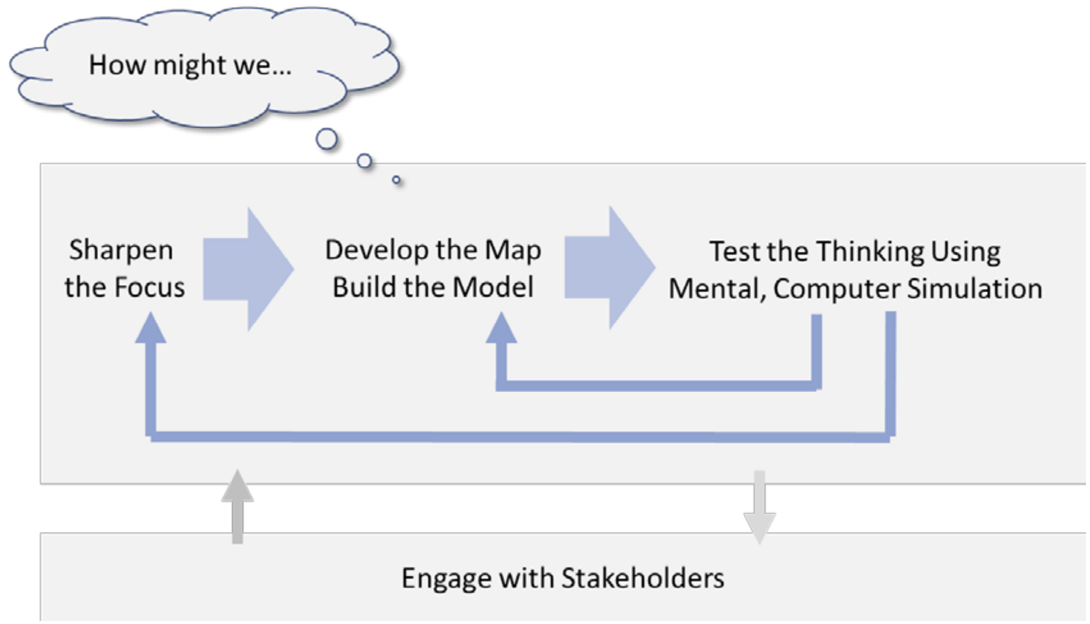
Eriksson O, Finnveden G, Ekvall T, Bjorklund A (2007) Life cycle assessment of fuels for district heating: a comparison of waste incineration, biomass- and natural gas combustion. Energy Policy 35(2):1346–1362

Source: Earles, J.M. and Halog, A., 2011. Consequential life cycle assessment: a review. *The International Journal of Life Cycle Assessment*, *16*(5), pp.445-453.

A quick look at the system dynamics approach

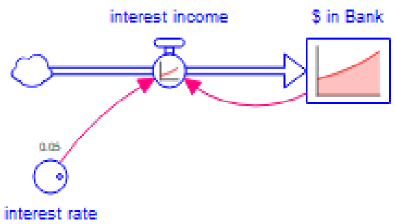
A DESIGN-FOCUSED PROCESS SUPPORTED BY A GRAPHICAL LANGUAGE

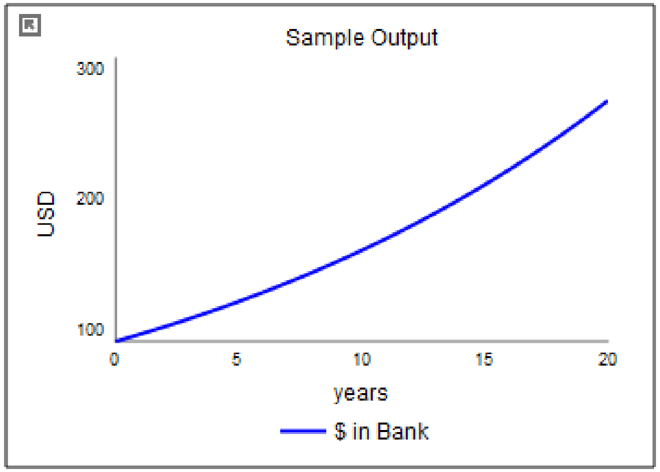
- Dynamics (disequilibrium focus)
- Stocks & flows (mass balance)
- Feedback loops (feedback-control systems)
- Broadened boundary of inquiry



Sources:
Peterson, S. (2010) Systems Thinking for Anyone: Practices to Consider. In J. Richmond, et al (Ed.), *Tracing Connections: Voices of Systems Thinkers* (pp. 31-51). ISBN 978-0-9704921-2-8
https://hbr.org/2008/02/make-better-decisions (accessed 2016-07-15)

A simple example





Equation Viewer - New Model

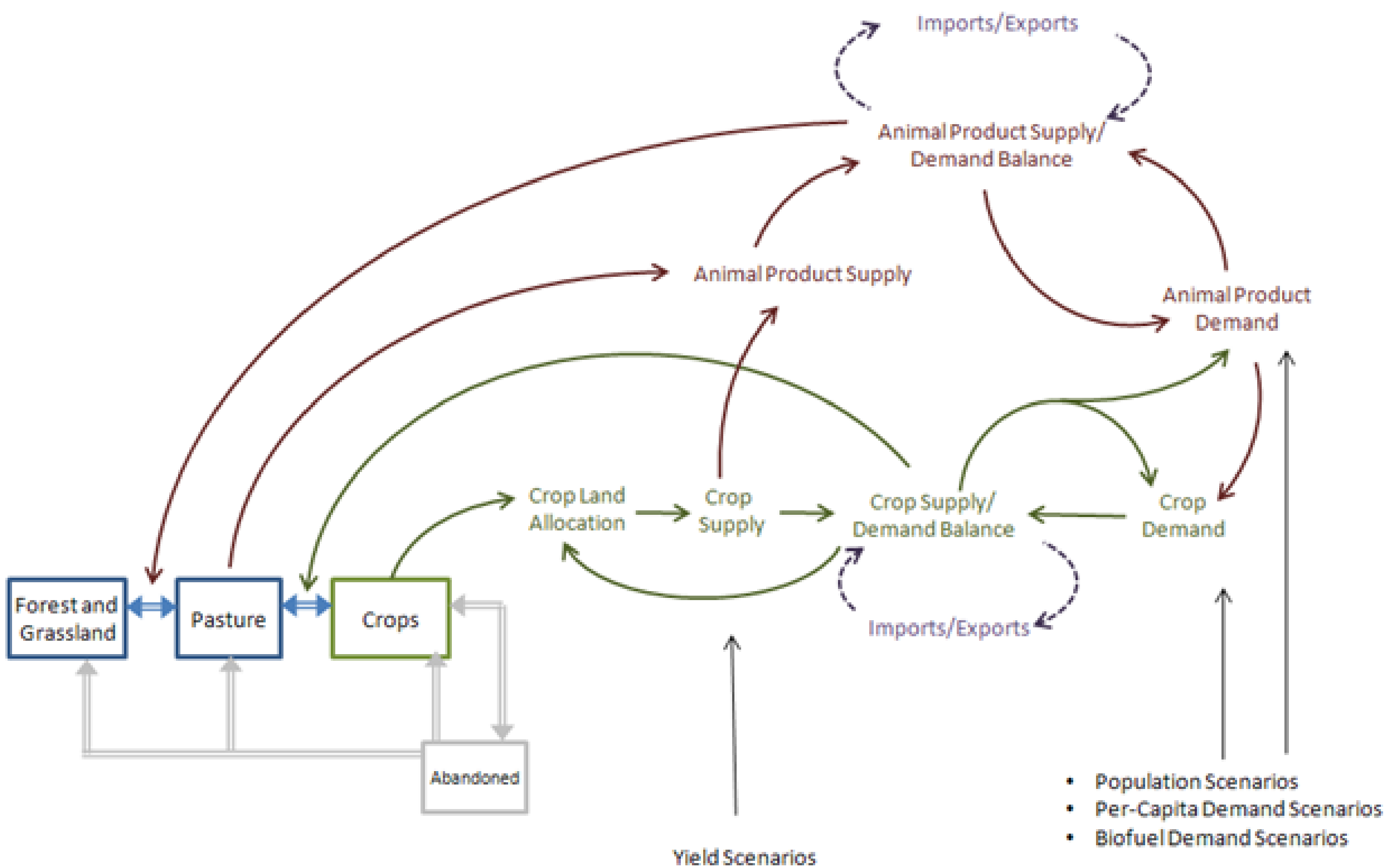
```
$_in_Bank(t) = $_in_Bank(t - dt) + (interest_income) * dt
    INIT $_in_Bank = 100
    UNITS: USD
    INFLOWS:
        interest_income = $_in_Bank * interest_rate
            UNITS: US Dollars Per Year
interest_rate = 0.05
    UNITS: 1/year
```

The BioLUC model

APPROACH

- System Dynamics Framework
  - Stocks/flows (land categories, crop inventory/production,use)
  - Feedback within and across stages in supply chain
- Modular, “Regional” model architecture
  - “Region” can reflect world, nation, geographical region, level of development, etc.
  - Enables rapid extension of model from 1 → 2 → n regions
  - Focus here on 2-region model; 18 region model available; 4 region model used for initial analysis of US/Brazil/China response to 2012 US drought.
- Reliance on GDP/capita scenarios and FAO data to drive dynamics around population, yield, food demand.
- Calibrate model against FAO datasets for land use and disposition.
- Possible to incorporate pricing dynamics into model. 2-region model uses “diffusion” mechanism to drive dynamics

BioLUC regional model structure



Source: Figure 1 from Modeling biofuel expansion effects on land use change dynamics
Ethan Warner et al 2013 Environ. Res. Lett. 8 015003 doi:10.1088/1748-9326/8/1/015003

BioLUC land, crop, animal categories and uses

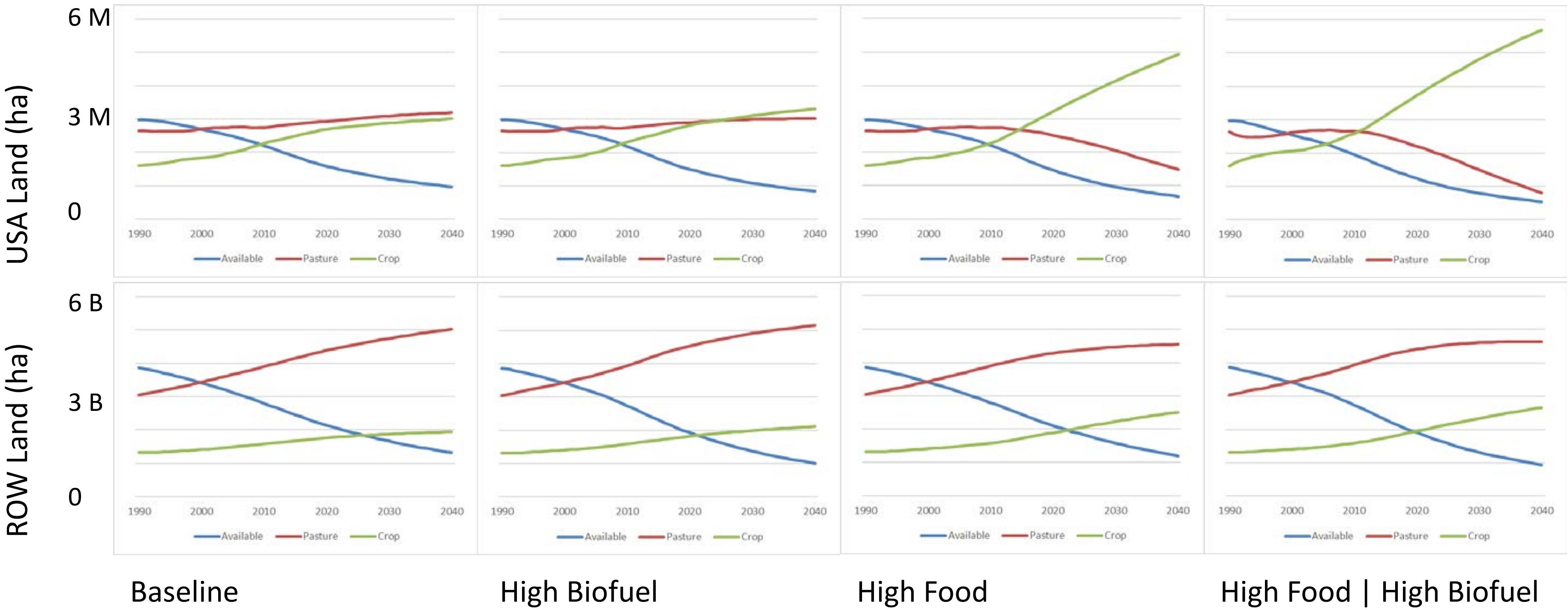
- 4 x 2 Land Bases
  - "Available" | Pasture | Cropland | Abandoned
  - Grassland | Forest
- 12 Cropland uses
  - Fallow
  - Forage
  - Fiber | Vegetable Fruit Nut | Other
  - Maize | Wheat | Rice | Grains NEC | Oil crops | Sugar
  - Energy Crops
- Four Animal Product Categories
  - Cattle/Sheep/Goat | Dairy | Swine | Chicken
- Induced demand from animal product to commodity crops, pasture, forage

BioLUC sample results from 4 scenarios

- Baseline: based on WAO projections to 2050
- High biofuels: 25% petroleum displacement
- High food: doubling of per-capita food demand
- High biofuels and food: 25% petroleum displacement and doubling per capita food demand

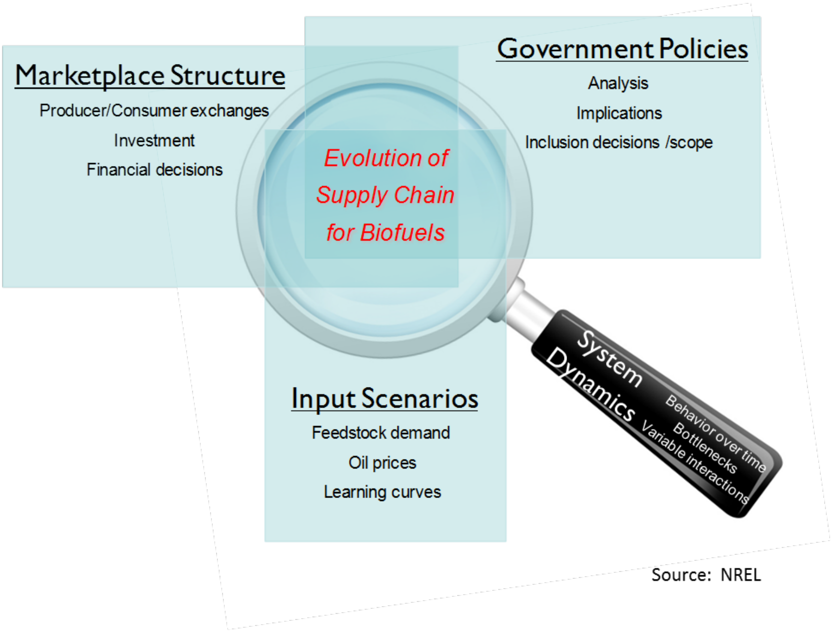
BioLUC sample results from 4 scenarios

1990-2040



Biomass Scenario Model

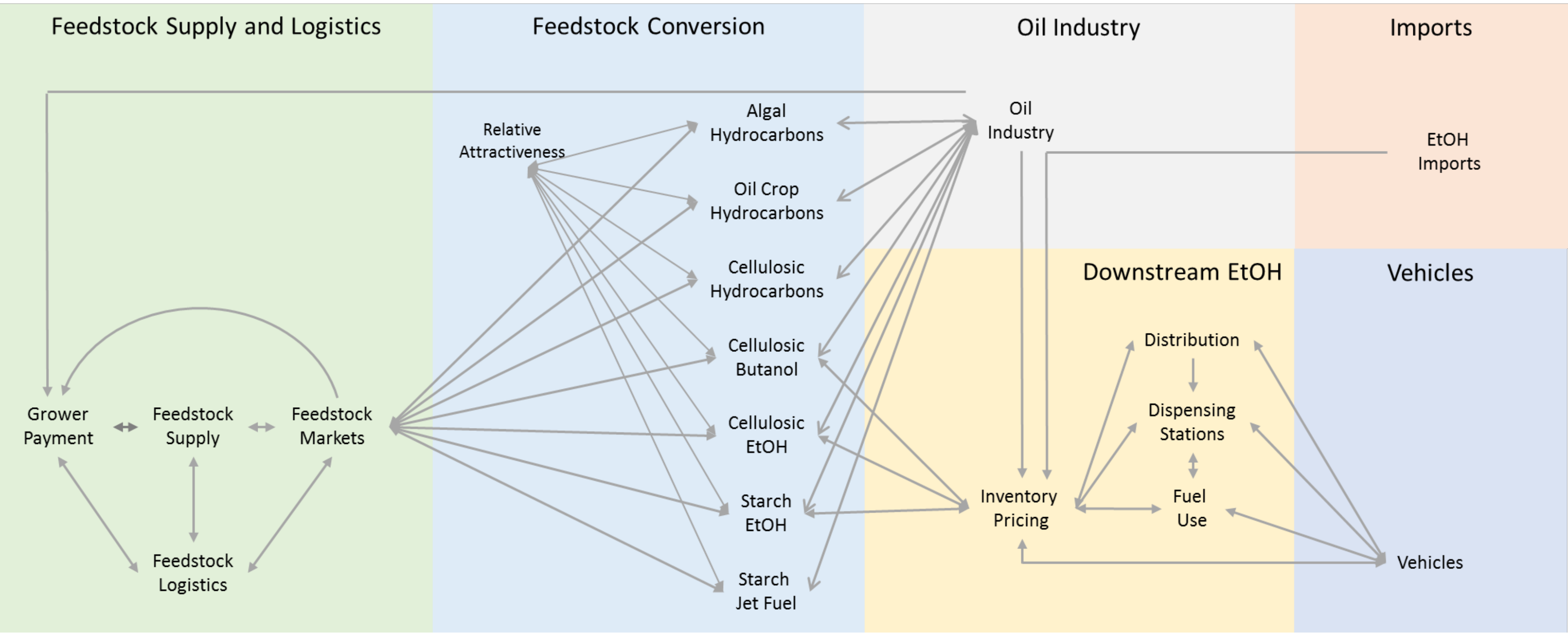
The Biomass Scenario Model (BSM) reflects a multi-year NREL effort aimed at developing an analysis platform for understanding how biofuels policy impacts the evolution of the U.S. biofuels supply chain.



Source: NREL

BSM Modular Structure

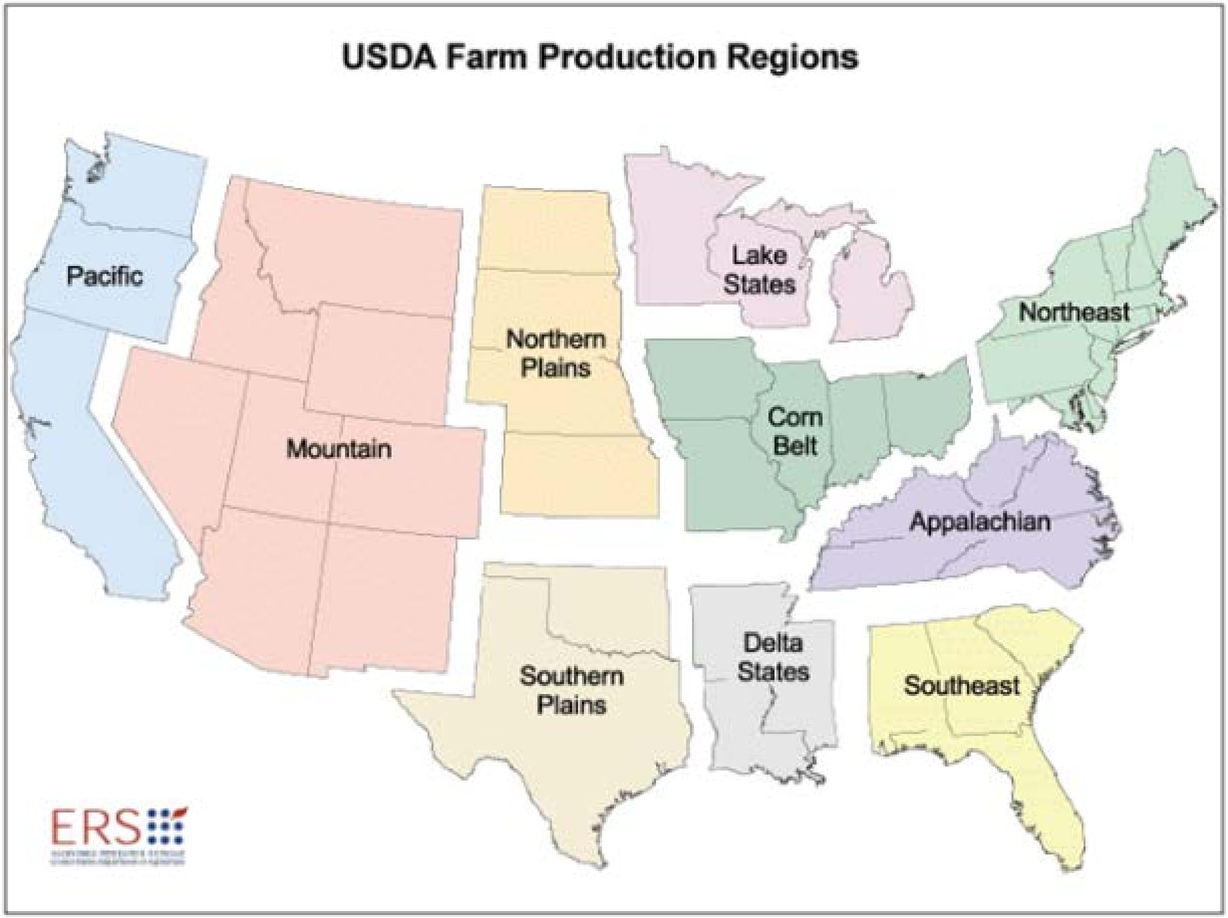
REPRESENTING THE SUPPLY CHAIN FOR BIOFUELS



Source: NREL

BSM Regional Disaggregation

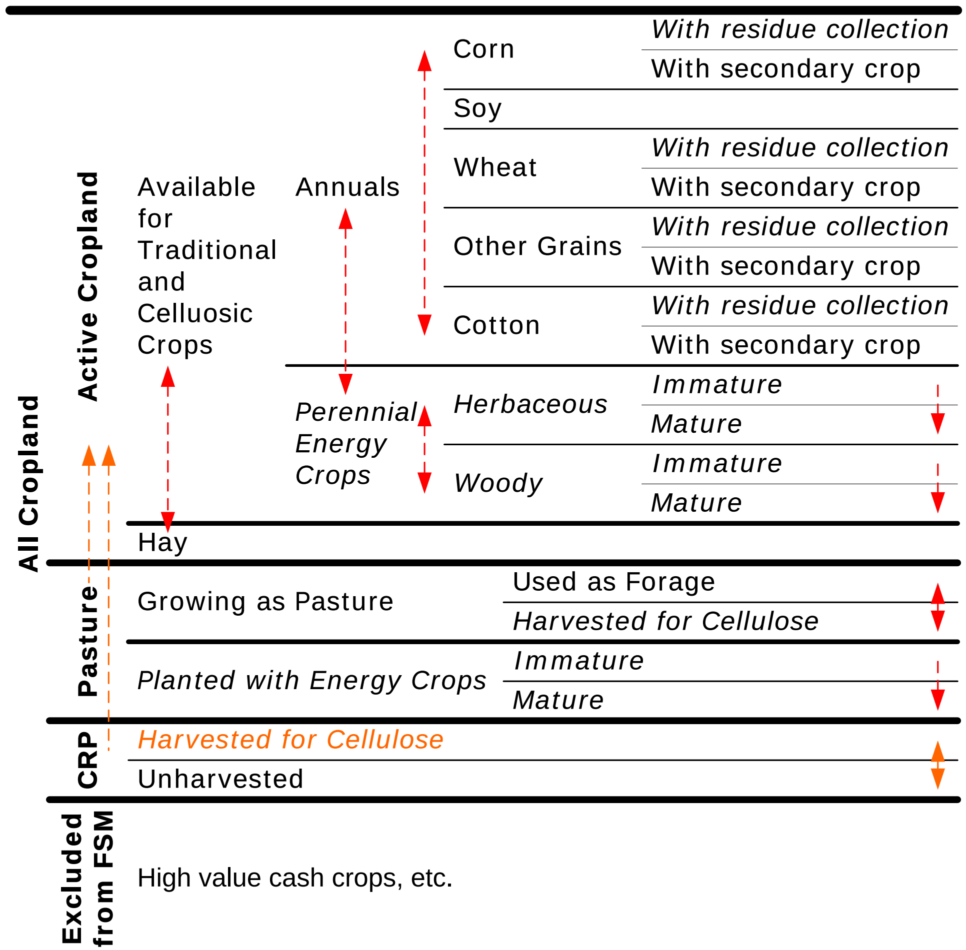
ENABLES REPRESENTATION OF REGIONAL PRODUCTION CONSTRAINTS



Source: NREL

BSM Cropland Categories

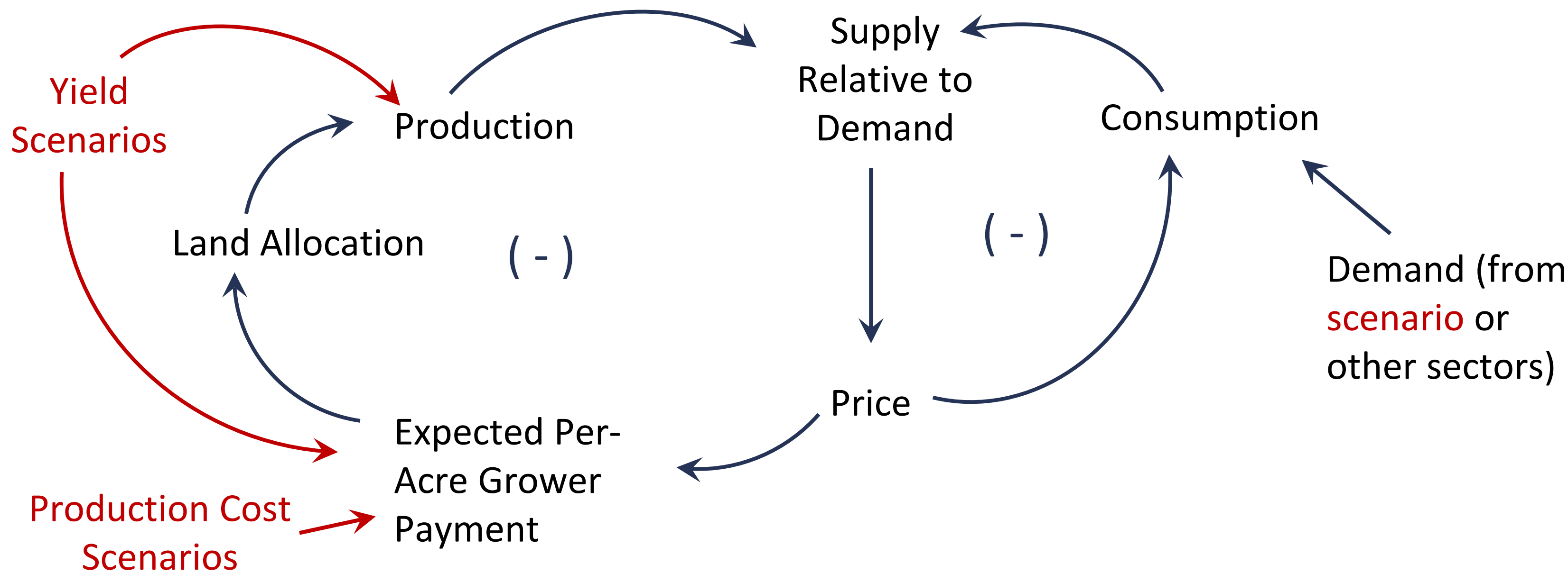
CROPLAND ALLOCATION BASED ON ECONOMICS (YIELD, COST, PRICE…)



Source: NREL

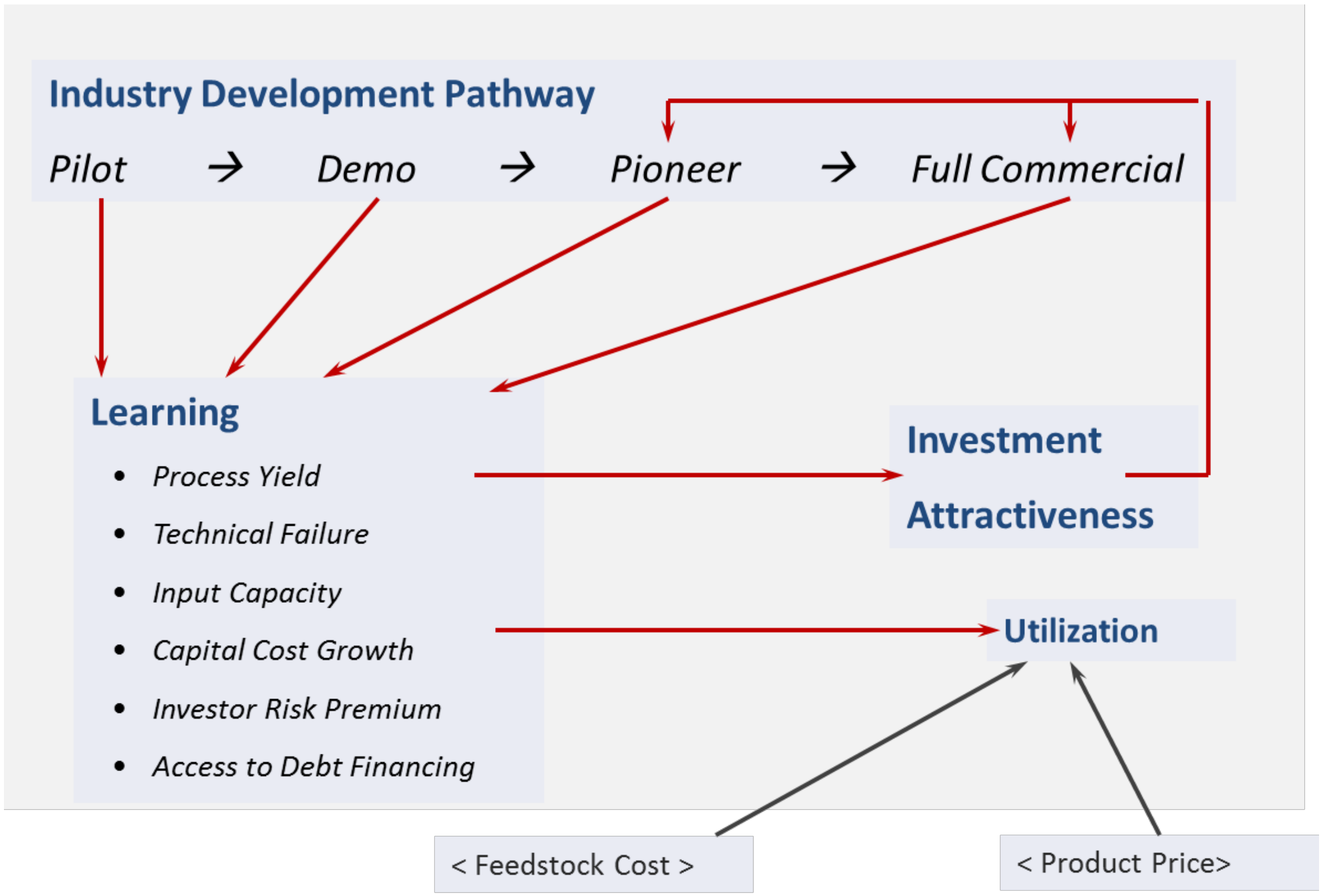
Price and Land Allocation Feedbacks

ENDOGENOUS PRICING-SUPPLY-DEMAND DYNAMICS



Source: NREL

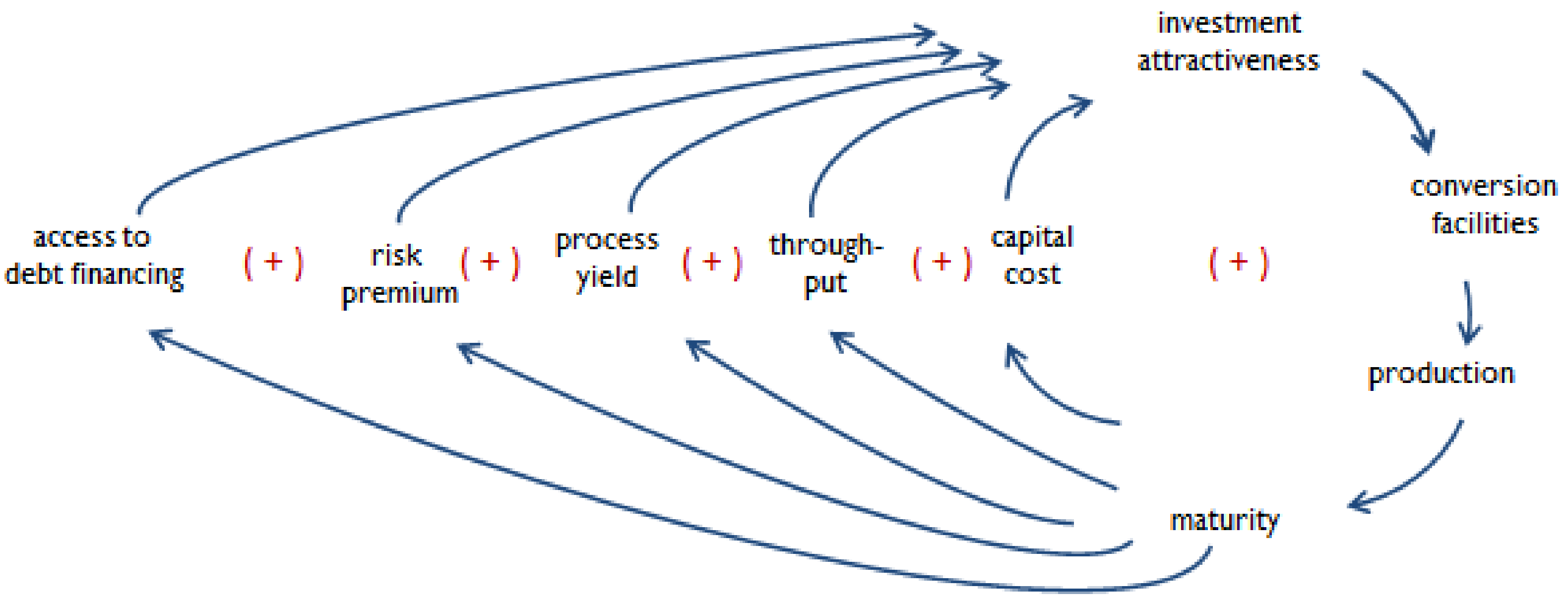
Key Interactions Within Conversion Modules



Source: NREL

Source: NREL

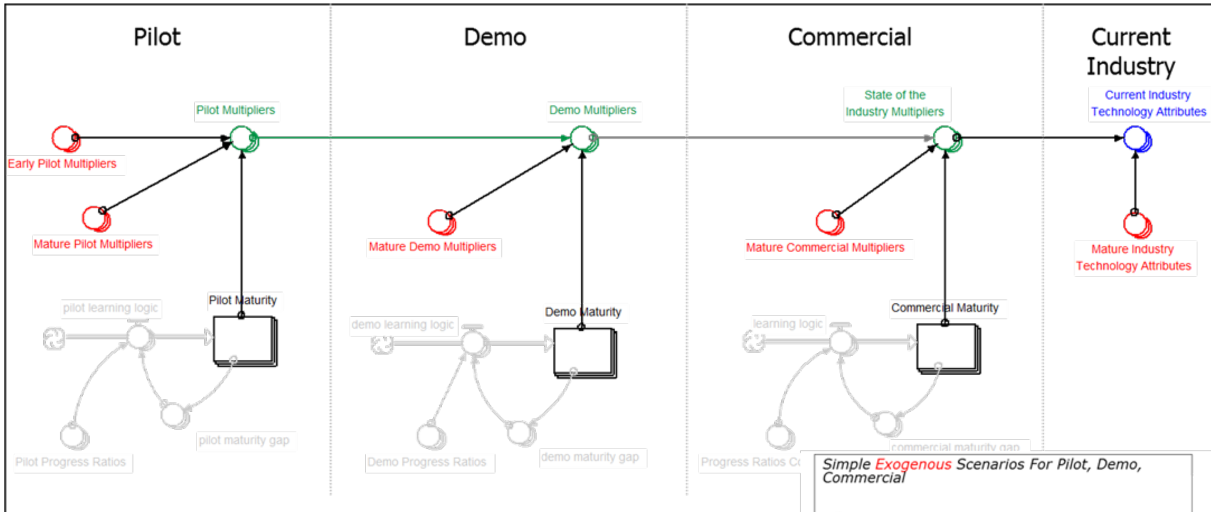
Key feedbacks around industrial learning

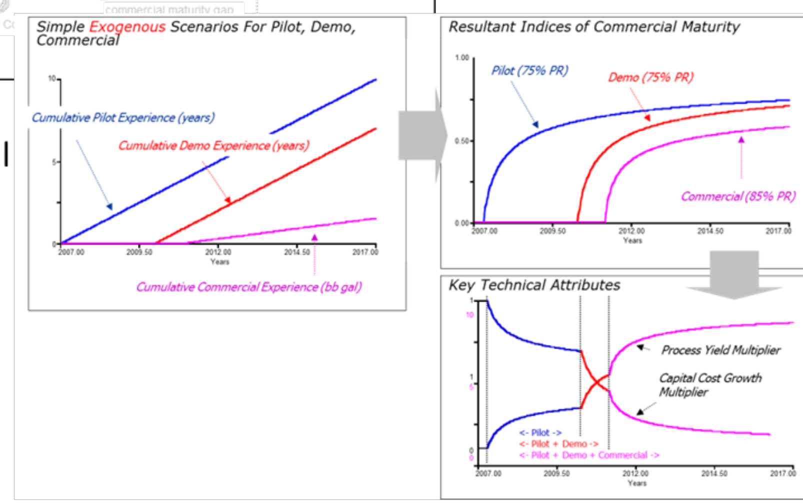


Source: NREL

Cascading Learning Curves

HOW DO YOU GET FROM LAB TO COMMERCIAL MATURITY?





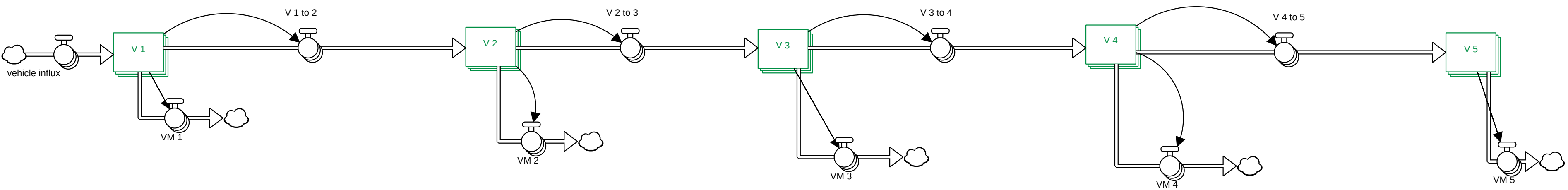
Benefits of staged approach

- Captures prior scale effects (important for capital cost growth)
- Explore implications of stage-specific progress rates as well as analysis of timing and placement of policy initiatives
- Maturity of technology stage affects multipliers, which affect cost of building and operating a commercial plant

Source: NREL

Vehicles

SIMPLE STOCK/VINTAGING MODEL THAT GENERATES FUEL DEMAND



- Vehicle influx driven by AEO data
- Possible to explore alternate vehicle scenarios (e.g., massive electrification, transition to new drivetrains, etc.)

Source: NREL

An experiment with BSM…

BASED ON AN ARTICLE SOME OF YOU MAY KNOW ABOUT

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Biotechnology

Cellulosic ethanol: status and innovation

Lee R Lynd[1,*], Xiaoyu Liang[1,*], Mary J Biddy[2], Andrew Allee[1], Hao Cai[3], Thomas Foust[2], Michael E Himmel[2], Mark S Laser[1], Michael Wang[3] and Charles E Wyman[4]

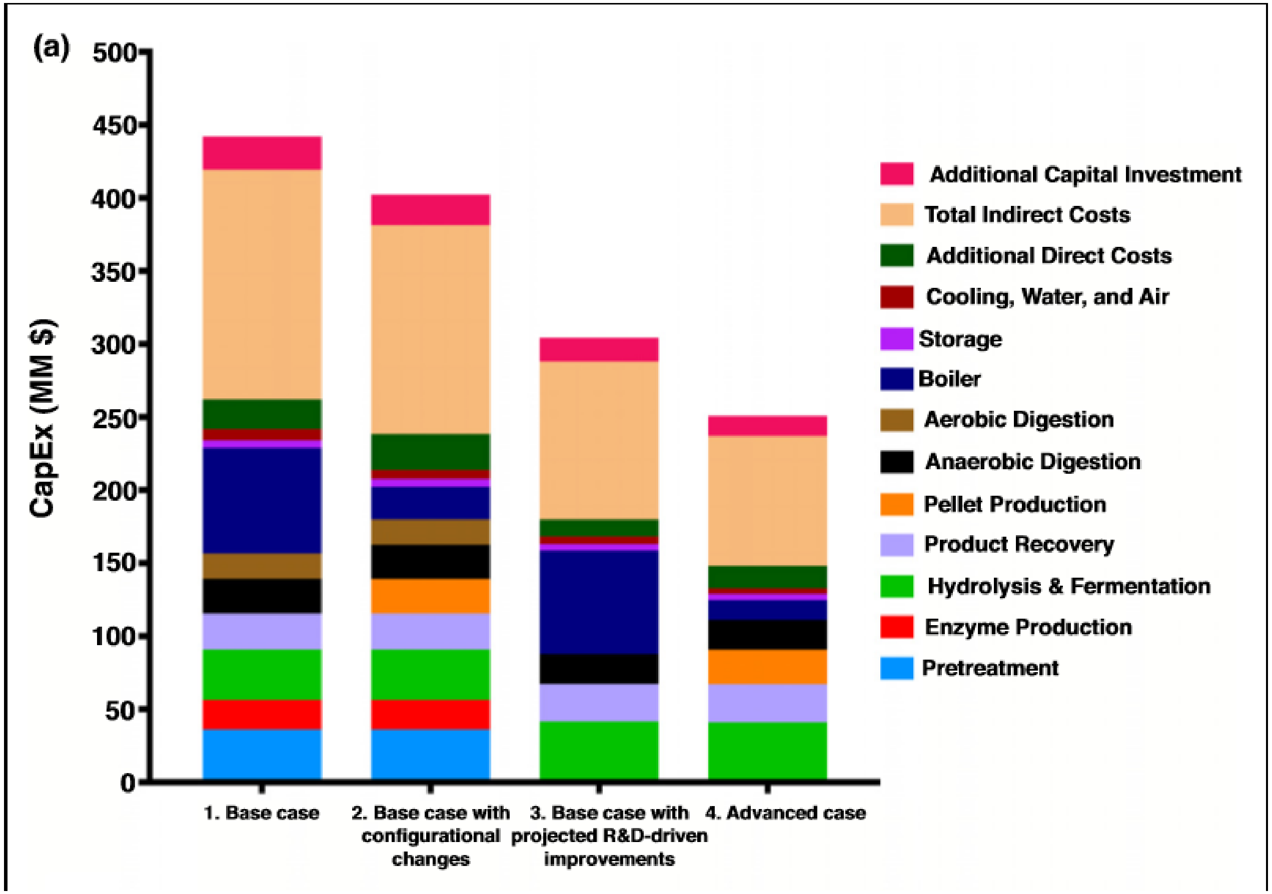
CrossMark

- With today's technology, conversion cost is high
- Cost reductions can be pursued with in-paradigm or new paradigm innovation
- Consolidated bioprocessing considered
- Potential for radically improved cost competitiveness via R&D-driven advances and configurational changes

An experiment with BSM…

LYND ET AL FIGURE 3A

Figure 3



An experiment with BSM-public…

SETUP

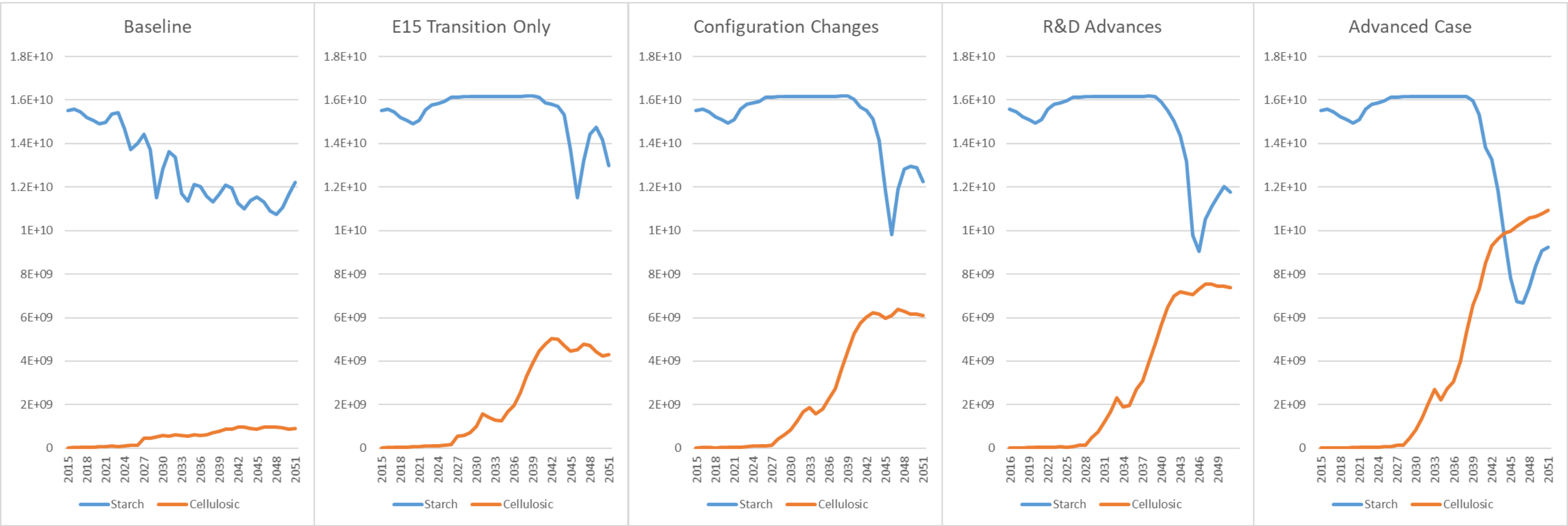
1. Baseline (Default BSM Settings)
2. Transition from E10 to E15
3. Transition + Configurational Changes
4. Transition+ Projected R+D advances
5. Transition + Advanced Case

	Parameter/case	1	2	3	4	5
nth plant technoeconomics	Thruput Capacity (Ton/day)	2205	2205	2205	2205	2205
(Case 1 uses BSM defaults)	Fixed Capital Investment (USD/yr)	471,000,000	471,000,000	400,000,000	320,000,000	270,000,000
(Case 2-4 estimated from Lynd et al 2017 Figure 3)	Fixed Operating Cost (USD/yr)	12,000,000	12,000,000	24,000,000	12,000,000	12,000,000
	Other Variable Operating Cost (USD/yr)	32,000,000	32,000,000	50,000,000	2,000,000	10,000,000
	Power Sales Revenue (USD/yr)	6,500,000	6,500,000	0	10,000,000	0
	Other Coproduct Sales(USD/yr)	0	0	50,000,000	0	60,000,000
	Process Yield (gal/ton)	79	79	79	79	79
Initial Maturity estimates	Pilot (unitless)	1.00	1.00	1.00	0.50	0.10
(Case 1 uses BSM defaults)	Demo (unitless)	0.80	0.80	0.50	0.10	0.00
(Case 2-4 Peterson estimates)	Commercial (unitless)	0.10	0.10	0.00	0.00	0.00
Pre-commercial activity start time	Pilot (yr)	n/a	n/a	n/a	2020	2020
(Peterson scenarios)	Demo (yr)	n/a	n/a	2022	2022	2022
linear transition from E10 to E15	Start (yr)	n/a	2020	2020	2020	2020
	Complete (yr)		2030	2030	2030	2030

Investment responsiveness factor	0.3 (0.5 in default)
RIN value	$1.20 USD
Oil Price Scenario	AEO Reference
Starch ethanol capacity	Limited to ~15 billion gal/yr

Sample Results

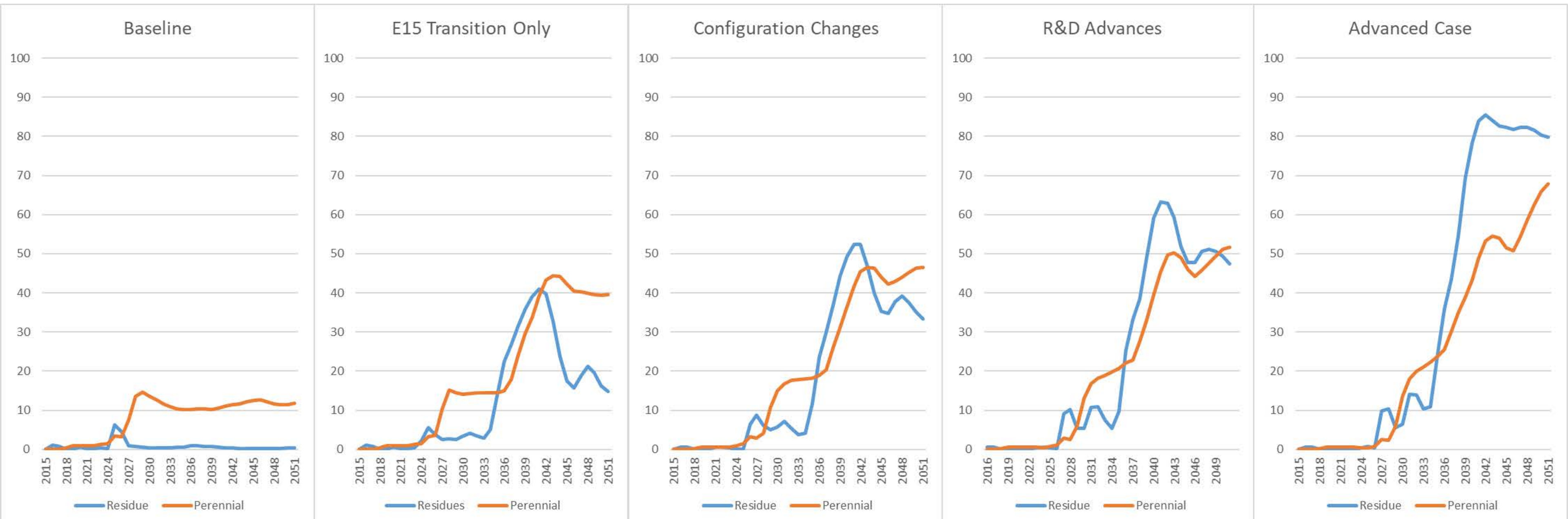
COMPARING CELLULOSIC AND STARCH INDUSTRIES ETHANOL PRODUCTION (GPY)



Production (BGY) in yr…	Baseline	E15 transition	Configuration	R&D	Advanced
2035	0.61	1.67	1.81	1.98	2.72
2050	0.90	4.32	6.11	7.37	10.09

Sample Results

CELLULOSIC FEEDSTOCK PRODUCTION (MILLION TON/YR)



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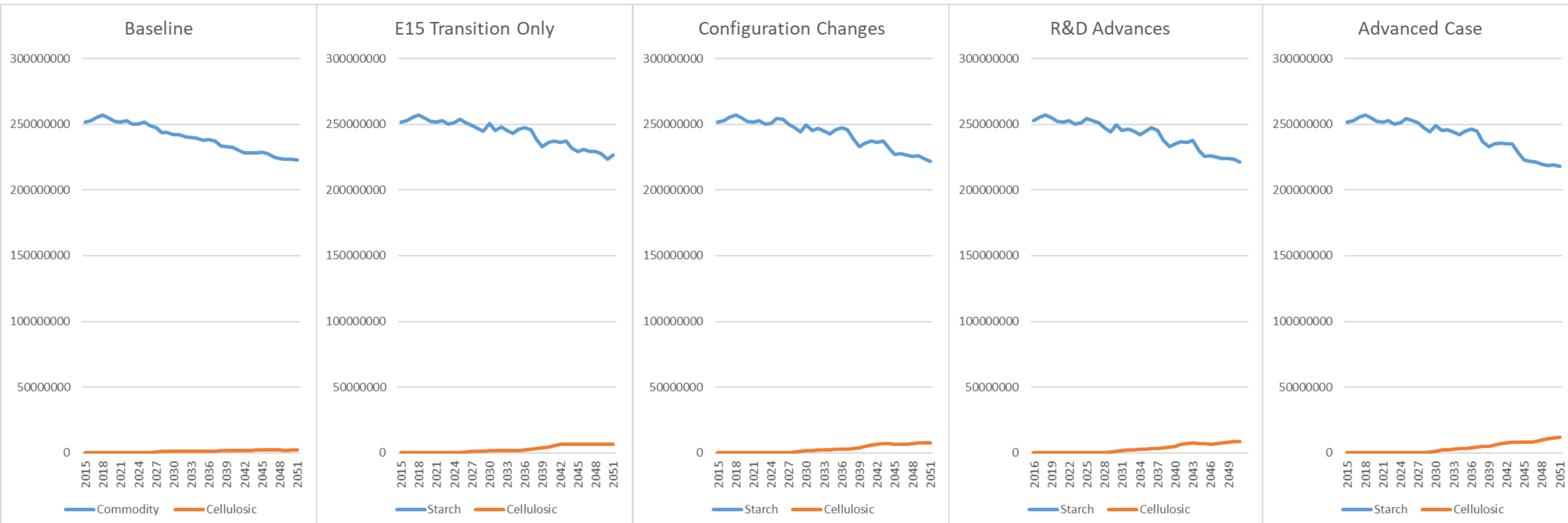
Sample Results

LAND IN PRODUCTION FOR COMMODITY CROPS, PERENNIAL CELLULOSIC FEEDSTOCKS (ACRES)



Cellulosic Acres in yr…	Baseline	E15 transition	Configuration	R&D	Advanced
2035	1,270,418	1,975,622	2,552,058	2,922,378	3,358,230
2050	2,033,276	6,589,232	7,747,774	8,581,541	11,712,170

Possible explorations

- Transition to E20 or higher EtOH blends
- Variations on pre-commercial investment scenarios
- Incentive and policy analysis
- Re-purposing of Starch ethanol industry
- Export market evolution
- Vehicle mix scenarios

Summary and Discussion

- BioLUC: Dynamic model focused on land use implications of population, food, biofuel pressures.
- BSM: Dynamic model focused on evolution of supply chain for biofuels in US. Multiple LCA-related avenues of inquiry.
- System dynamics: Framework and language with potential to address challenges in LCA analysis
  - Spillover effects, rebound effects, indirect 2nd and 3rd order interactions
  - Feedbacks such as experience curves
  - Stocks and flows
  - Dynamics/disequilibrium phenomena