Land Use Change and Integrated Modeling for Sustainability Analysis

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“Seeking sustainable pathways for land use in Latin-America”
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Land use: The ultimate human-environment interaction

Over 50% of the ice-free surface of the Earth has incurred significant human-induced land-cover change

- Land-climate interactions
- Water quantity and quality
- Biotic diversity, ecosystem function, and trade-offs among ecosystem services
- Food and fiber production
- Energy and carbon (sequestration)
- Urbanization, infrastructure, and the built environment
Cultivated Systems in 2000 cover 25% of Earth’s terrestrial surface

- More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850
- Cropland is decreasing in developed countries and increasing in developing countries
- Net global area of irrigated cropland has increased by 2,400% over the last 200 years
Deforestation Hot Spots

- Estimated tropical deforestation annual rates of 1.4 – 3.3% worldwide
- Reforestation occurring in Europe and regions of the US, while deforestation due to logging, cropping, and livestock grazing is occurring in tropical regions
Proportion of land cover in urban by global land cover class
- Coastal zones: 10.2%
- Cultivated areas: 6.8%
- Islands: 4.7%
- Inland waters: 3.2%

Only 2-3% of global land cover is urban, but 46% of world’s population resides in an urban area (25% reside in cities 1-5 million, 6.7% reside in megacities of 10 million+)
- Most populated cites are along coastlines and waterways
- Fastest growing cities are in developing countries
- Ecological impact of urbanization is much greater than just the amount of urban land
Water

- 5 to possibly 25% of global freshwater use exceeds long-term accessible supplies (*low to medium certainty*)
- 15 - 35% of irrigation withdrawals exceed supply rates and are therefore unsustainable (*low to medium certainty*)
What is sustainable land use?

The Brundtland Commission Report, Our Common Future (1987) defined **sustainable development** as...

“development that meets that needs of the present without compromising the ability of future generations to meet their own needs .... At a minimum, sustainable development must not endanger the natural systems that support life on earth.”

...requires making trade-offs between resource use now and in the future
How can we assess future trade-offs in a world of uncertainty?

- Population Growth?
- Migration?
- GDP?
- Energy Costs?
- Non-Energy Costs?
- Availability?
- Technological Change?
- Climate Change?
- Ecological Degradation?
- Political leaders?
- Natural resource conflicts?

Adapted from: Richard Moss (2014), Joint Global Change Research Institute
Predicting the future is risky business

Population Growth? Migration? GDP?


Climate Change? Ecological Degradation?

Political leaders? Natural resource conflicts?

Adapted from: Richard Moss (2014), Joint Global Change Research Institute
Scenarios: Human & Natural Conditions

- Population
- Income
- Migration
- Technology
- Markets
- Policies
- Social values
- Climate change
- Water resources

Integrated Model

Changes in Land Use and Land Cover

- Agriculture
- Urban
- Forest
- Wetlands
- Impervious surface
- Fragmentation

Integrated Model

Environmental, Economic, Social Impacts

- Climate change
- Water quality
- Economic growth
- Livelihoods
- Public health
- Social interactions

Evaluation criteria

Is change sustainable?
Integrated models: Represent interactions between humans and natural systems

Nature impacts human well-being

Humans impact nature
Assessing sustainability: Weak versus strong sustainability

• Weakly sustainable: does change generate non-decreasing total wealth over time?

\[ \Delta W_t = \text{Value of } \Delta \text{ produced capital}_t (v_{PC} \cdot \Delta PC_t) + \text{Value of } \Delta \text{ natural capital}_t (v_{NC} \cdot \Delta NC_t) + \text{Value of } \Delta \text{ human capital}_t (v_{HC} \cdot \Delta HC_t) + \text{Value of } \Delta \text{ social capital}_t (v_{SC} \cdot \Delta SC_t) \geq 0 \]

• Strongly sustainable: are minimum critical natural capital stocks and flows?

\[ NC_{i,t+1} = NC_{i,t} + \Delta NC_{i,t} \geq \overline{NC}_i \text{ for each critical NC stock or flow } i \]
Key aspect on integrated models: Modeling land use change

- **Land use conversion**: Discrete change from one land use category to another (example: forest to agriculture; agriculture to urban)

- **Land use modification**: Changes that affect the character of the land without changing the classification (example: intensification of agriculture)

- **Land management change**: Changes in the way in which land is managed, (example: fertilizer and pesticide use by farmers, zoning laws for urban development)

- **Land cover versus land use**
Land use change is the outcome of human decision making

Maumee watershed, Ohio land use data: field-level crop rotation (2006-2009)

Legend

Crop Rotation (2006 to 2009)
- Continuous Corn (3 or 4 years)
- Continuous Soybean (3 or 4 years)
- Corn-Soybean Rotation
- Corn-Soybean-Wheat Rotation
- Continuous Hay or C-S-H Rotation
- Other Types of Crop Rotation
- Other Rural Land Uses

Source: Common Land Unit boundaries overlaid with the Cropland Data Layer (USDA), 2006-2012
Land use change is the outcome of human decision making

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Economic models of land use

• Models based on **individual decision making** (firms, households)
  • Land use decisions: landowner (e.g., farmer, developer)
  • Location decisions: firms and households

• Model solution: relates **individual-level decisions to aggregate outcomes of prices and land use pattern**
  • How do aggregate market-level outcomes—such as land prices, land use patterns—result from cumulative individual decisions and interactions?
  • How do aggregate/market outcomes influence individual decisions?
Individual decision making agent

• Agents face constraints → necessitates trade-offs
  • Resource scarcity, other environmental constraints; income, time constraints; policy, legal constraints
  • Opportunity costs matter

• Agents make location and land use decisions to make themselves better off
  • Maximize expected profits or utility

• Agents consider benefits and costs of existing and alternative states in current and future periods
  • Uncertainty over future outcomes → expectations over future outcomes influence current decisions
Economic modeling challenges
(roughly in order of difficulty!)

1. **Identification**: Controlling for unobserved correlation and other sources of bias to isolate causal effect
2. **Prices and spatial equilibrium**: Accounting for price formation and feedbacks
3. **Data data data...**
4. **Non-economic behavior**: Accounting for heterogeneity in motivations, beliefs, decision-making rules
5. **Cross-scale integration**: Aggregating, downscaling, and modeling interactions across local-to-global scales
6. **Ecological dynamics**: Modeling coupled dynamics, nonlinearities and the value of resilience
Challenge #4: Non-economic behavior

• Traditional economic models usually impose assumptions such as profit maximization rather than test them.

• Differences in behavior are important – differences not only in preferences and expectations, but also in beliefs, motivations and decision making rules.

• Accounting for these behavioral differences is critical for scenarios in which the goal is to predict land use responses to a change in policy.
Example: Understanding heterogeneous farmer decision-making in Ohio

• All farmers want to maximize profits, but...

• When asked about primary farming goal, 80% chose non-economic motivations such as environmental stewardship, family succession, and maintaining a rural lifestyle (Ferry and Wilson 2010)

• Farmers’ environmental stewardship is a positive significant driver of farmers that adopt no-till (Konar et al. 2012) and filter strips (Howard and Roe 2013)

• Farmer’s perceived efficacy matters (i.e., filter strip effectiveness in reducing runoff) matters more for “status quo” farmers versus farmers in “environmental stewardship” class (Howard and Roe 2013)
Challenge #5: Cross-scale integration

Determinants of Land Use and Land Use Change

- Climate change, economic restructuring, global politics & conflict
- Trade & migration flows, transportation and communications costs
- Household wealth & poverty
- Public services, infrastructure, local policies
- Regional migration & production
- Urban & natural amenities, public services, infrastructure, local policies
- Neighborhood quality, zoning, congestion, accessibility, air quality, water quality, land conflicts
- Soil quality, access to roads, amenities, surrounding land uses
- Living costs, agglomeration economics, regional migration & production

Source: Pickett et al. 2011
Challenge #5: Cross-scale integration

Determinants of Land Use and Land Use Change

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- **Multi-sector, migration, firm location models**
- **Spatial models of locational choice, land use**
- **Global integrated assessment, multi-sector models**

Key influences:
- Climate change, economic restructuring, global politics & conflict
- Household wealth & poverty
- Living costs, agglomeration economics, regional migration & production, public services, infrastructure, local policies
- Soil quality, access to roads, amenities, surrounding land uses
- Neighborhood quality, air quality, land conflicts
Challenge #6: Ecological dynamics

Ecosystems responses to climate change, habitat fragmentation and other impacts are often nonlinear; characterized by **thresholds and regime shifts**, e.g., fisheries collapse, lake eutrophication, species loss

**Example: Lake Erie**

- Land use in the watershed results in increases in sediment, nutrients (fertilizer and sewage) and pesticides
- Nutrient runoff leads to lake eutrophication (excessive plant growth)
- Results in “sudden” harmful algal blooms and dead zone
Lake Erie-land water integrated modeling

Policy support
(surveys of Ohio residents, Maumee farmers, residents)

P policies
Farmer land management decisions

P runoff from field into watershed
P loadings to Lake Erie

Spatial land-watershed simulation model with SWAT (data on 187k rural land parcels, 2300 HRUs)

Lake hydrodynamic-lower food web model and statistical models
Changes in ecosystem services

Econometric models of crop choice, fertilizer demand & BMP adoption
(survey of 7,500 farmers)

Costs of policy ($)
Benefits of policy ($)

Improved ecosystem services
Non-market valuation (survey of anglers, Ohio residents)
Conclusions

• This is a LOT of work – it will take a long time to fully address these challenges and we will never get everything “right” – is it really WORTH IT?

• Policy decisions must be made – better to make them with as much scientific input as possible!

• In the words of George Box (1987), one of the most influential statisticians of the 20th century, “all models are wrong, but some are useful.”

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Conclusions

• Economists play a critical role in
  • Modeling human behavior
  • Designing incentives for individuals and businesses to provide ecosystem services
  • Valuing ecosystem services

• But economists can’t do it alone
  • Biophysical scientists: integrated models
  • Other social scientists: non-economic behaviors
  • Policy makers: what’s feasible
Trade-offs between P runoff and water quality

- **Farmer benefits** of P runoff = avoided cost of implementing BMP’s (best management practices)

- **Social costs** of P runoff = foregone benefits of improved water quality

![Diagram showing trade-offs between P runoff and water quality with MC to society and MB to farmer lines intersecting at P*]
Trade-offs between P runoff and water quality

- **Farmer benefits** of P runoff = avoided cost of implementing BMP’s (best management practices)

- **Social costs** of P runoff = foregone benefits of improved water quality

- **If the threshold were deterministic and we could perfectly control P**, then the value of resilience = 0 for P < Threshold
Trade-offs between P runoff and water quality

- **Farmer benefits** of P runoff = avoided cost of implementing BMP’s (best management practices)

- **Social costs** of P runoff = foregone benefits of improved water quality

- However, loss of resilience increases prob of regime shift → this cost is reflected in increasing MC curve as P approaches threshold
Valuing Resilience (Gören-Mäler and Li 2010)

- Resilience can be regarded as one of society’s productive capital stocks. **Value of resilience depends on**

1. **How a change in resilience alters the probability of a regime shift in a future time period** given initial level of resilience (requires projection of system dynamics in future time periods)
2. **Difference in intertemporal net social benefits** between state 1 (good) and state 2 (bad): $NB_1 - NB_2$

![Graph showing probability of future regime shift from state 1 to 2 in period t+s for each of the three scenarios (given $R_t^0$)](attachment:image.png)

- Probability of future regime shift from state 1 to 2 in period t+s for each of the three scenarios (given $R_t^0$)

- t Future time periods t+s