SUSTAINABILITY SCIENCE AND TROPICAL AGRICULTURE

JAMES RISING

The participants for the group project decided to go separate ways, but this class has had a considerable, if nascent, impact on my research directions. Below, I explore those connections.

The seminar in sustainability science helped me identify more clearly and practically the intersection of ideas I hope to discuss in my thesis. I plan on applying my interest in complex systems to the social dynamics behind of tropical agriculture, with an eye toward identifying leverage points. Tropical agriculture is not an area I have much familiarity with, so I am partly using this paper as an exercise to learn about more of its issues. I focus on the generalities of global practices, particular around slash-and-burn agriculture, recognizing that the dynamics and drivers can vary greatly between regions. In this paper, I make a number of estimates, fill in some of the items in the SES framework, and build a simple model. All of these are meant to be rough attempts, to be explored more fully at another time.

A wide range of the society-wide behaviors that drive climate change and environmental degradation are characterized by complexity and overdeterminedness. Deeply embedded social structures and conventions mutually reinforce the status quo, so that individual action or isolated policy changes are difficult and costly. However, the interlocking feedback loops and non-linearities of complex systems suggest that, in addition to reinforcing drives, there are hidden "leverage points", places where small adjustments can amplify into system-wide changes (Meadows, 1997). I hope that by integrating system dynamics modeling with spatial and network techniques, I can uncover these structures in systems characterized by multiple drivers and spatial heterogeneity.[1] Good candidates for this approach include agricultural practices in poor countries, passenger transportation, some public health issues like obesity and substance abuse, and commons resource problems like groundwater use and fishery management, as well as situations fraught with rebound effects and environmental standards that shift activity across borders (e.g., carbon leakage).

Agriculture is amongst the most pressing issues in sustainable development, for its significance for growth, impacts on the environment, and changing needs in the future. The environmental impacts of current agriculture include land use change (80% of new cropland is replacing forests) and the resulting carbon release (12% of anthropogenic CO_2 emissions), eutrophication and pesticide pollution, and water overuse (Foley et al., 2011). Worldwide agriculture demand is expected to double between 2005 and 2050, pressing these systems further (Tilman et al., 2011).

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[1] In this way, my research bridges the gap between the political arena of sustainable development and the scientific realm of sustainability science. While the rhetoric of sustainability science places it firmly within academia, my research is directed toward identifying appropriate actions.

These issues are of particular concern in the tropics. Human need is great (Bloom et al., 1998). Potential for biodiversity loss is enormous (Wiens and Donoghue, 2004). The huge number of small-holder farmers and weak governments make enacting policy difficult (for example, in South Asia, over 95% of farmers have 2 ha or less (Shah et al., 2003)). Low soil fertility and the slash-and-burn practices used to combat it (at the expense of high erosion rates), have locked many into destructive practices and poverty traps. A wide range of new practices (Bank, 2007) and new technologies (such as slash-and-char (Lehmann et al., 2002)) have been slow to make an impact. REDD agreements offer hope, but governments are likely to have a difficult time enforcing the behavior changes in resource-strapped areas.

The inclusive wealth approach is of limited use for this research. It does not capture how individuals or larger communities make decisions nor offer alternatives. As a method for evaluating alternatives, inclusive wealth will be useful if the effective costs of pushing on various leverage points can be quantified. For example, if a certain leverage point involves constructing an information feedback loop, this can be symbolized as an increase in institutional capital, at a cost of effort.

Analytically, let $\hat{L}_i(t)$ be an intervention in the form of a plan of investment over time into capital stock i, and $\hat{p}_i(t)$ be the price of that capital– not the shadow price, but the personal price to the implementing institution. Define

$$\hat{V} = \int_0^\infty \left(U(C(K(t))) - \hat{p}_i(t)\hat{L}_i(t) \right) e^{-rt} dt$$

such that

$$\frac{dK_j(t)}{dt} = \begin{cases} f(C(K(t)), K(t)) \text{ if } j \neq i \\ f(C(K(t)), K(t)) + \hat{L}_i(t) \text{ if } j = i \end{cases}$$

Here, rather than defining $V(K)$ as the optimal path of consumption, I posit a model of consumption, as a function of stocks, $C(K)$.[a] The consequence of the original theory that $\frac{dV(K(t))}{dt} = \sum_{j=1}^{N} p_j(t) I_j(t)$ remains unchanged.

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[a] In this formulation, $U(C)$ is a social welfare function defined by an individual institution. This better respects Arrow's Impossibility Theorem.

Agriculture might benefit from an industrial ecology perspective. In developed countries, agriculture is widely considered to be like manufacturing, taking inputs (mostly N, S, and P) and converting them to food outputs and externalized pollution. Even though sustenance farmers do not approach their work as an industry (and many tropical farmers do not purchase inputs), their behaviors form a defacto product life cycle. Anderson (1990) describes such a closed-cycle analysis for Nitrogen in traditional Chinese farming. The formation of closed-loop processes can improve efficiency and decrease environmental degradation. This kind of new agricultural ecology is exemplified by Joel Salatin's Polyface Farm, where six species of livestock form interconnected closed processes (see figure 1) (Pollan, 2006).

From the perspective of tropical farmers, the rainforests form a Social Ecological System, and the full wealth of thought around SESs is applicable. Governments, small- and large-holder farmers, and farming institutions are all actors and stakeholders. As a case study

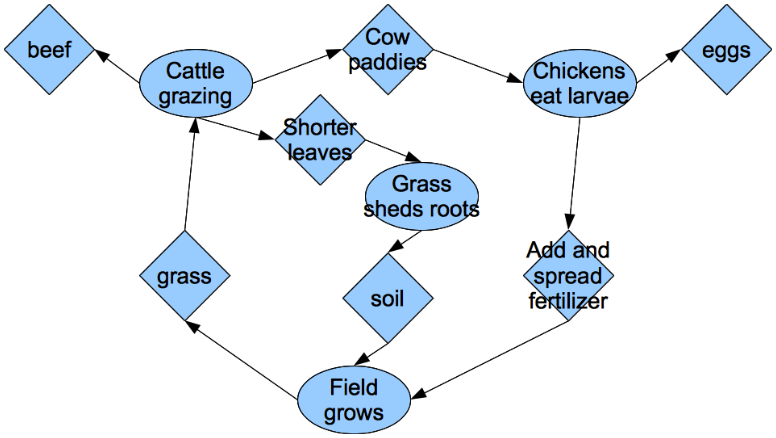

Figure 1. Diagram of the some of the circular economies described in Pollan (2006). Ovals denote processes, which take and produce products or ecosystem services (diamonds).

in applying the SES framework, some of the elements of a slash-and-burn SES system are enumerated below:

Resource Systems (RS)	
RS2 - Clarity of system boundaries	Low. Few property rights, and no clear boundaries around tropical forests.
RS3 - Size of resource system	Worldwide: 12.4 million km^2, 1.5 million km^2 over-harvested (see figure 2)
RS5 - Productivity of system	∼ .5 metric tons/ha-decade (Dove, 1983)
RS6 - Equilibrium properties	Optimal rotation given by the Faustmann formula; see sister paper for more analysis[2]
Resource Services and Units (RSU)	
RSU1 - Resource unit mobility	Trees have low mobility, but harvested nutrients drain quickly.
RSU2 - Growth and replacement rate	Decades
RSU3 - Interaction among resource units	Density-dependent tipping points (locally (Sheil and Murdiyarso, 2009) or at 30% (Coe et al., 2009) - 40% (Nobre and Borma, 2009) loss
RSU4 - Economic value	∼$220 ha/year (2011 $, PPP)
Actors (A)	
A1 - Number of actors	Worldwide: 240-300 million (Dove, 1983)
A2 - Socioeconomic attributes of actors	Generally poor, subsistence farmers
A3 - History of use	Sustainable until recent decades
Action Situations: Outcomes (O)	
O1 - Social performance measures	Poverty-traps common
O2 - Ecological performance measures	Over-harvesting in over-populated areas; soil loss; habitat fragmentation; biodiversity can be maintained.
O3 - Externalities to other SESs	Carbon release; potential tipping points

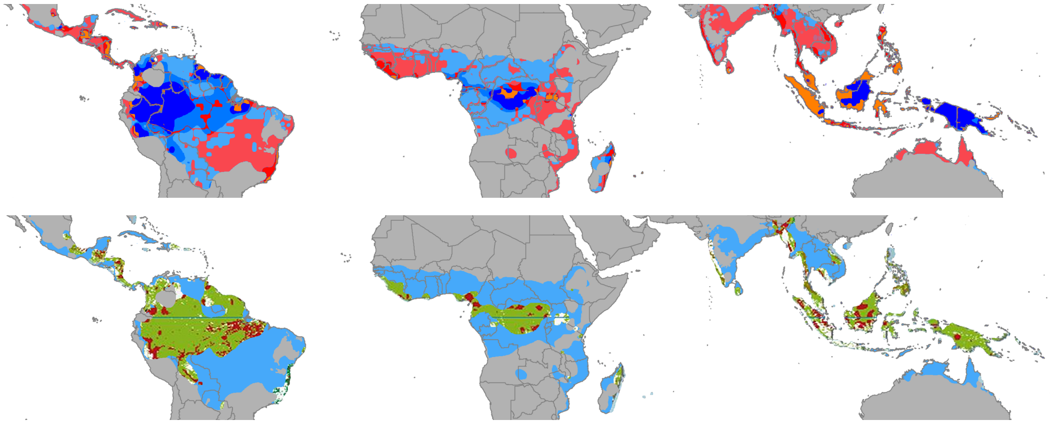

Figure 2. Attempts to identify slash-and-burn regions. (1) The top map shows in shades of blue regions of tropical climate (Köppen climate zones Af, Am, and Aw) where cropland is present but less than 10% of land area, according to Ramankutty and Foley (1998). This is the range at which slash-and-burn agriculture is sustainable. Shades of red denote tropical climate zones for which cropland is either absent, or greater than 10% (and therefore not sustainable slash-and-burn agriculture). (2) The bottom map shows in red the regions of the the Af and Aw Köppen climate zones that have had net deforestation (data from the Millennium Ecosystem Assessment, analysis by WRI). These are tropical regions where human activity has not managed the rainforests sustainably.

Boundary organizations are important to mediate the needs of farmers and the global drive to preserve biodiversity and curb climate change. Farmers have a wealth of information about forest dynamics and sustainable farming practices, but also can benefit from scientific knowledge. For example, scientists can provide soil health indicators and ENSO predictions, offer new technologies, and identify cross-scale effects.

Slash-and-burn degradation is essentially a cross-scale effect. Local interactions, by individual farmers, have the potential to produce large-scale consequences, not only as a sum of their clearings, but because farmers interact by spreading transportation networks, and through regional climate and ecological tipping points. The dynamics of rainforests are themselves a study in complexity. They are non-linear, heterogeneous, historical, and built on complex ecological networks.[3]

Trade-off exist between land use options, and can only be fully explored with spatially explicit models. Many use patterns are currently simultaneously suboptimal on economic and ecological grounds (e.g. Polasky et al., 2008). Two references suggest opportunities to find win-win situations for poor farmers and their environment. First, slash-and-burn farming may be able to support more people than management of a forest for wood (Dove, 1983)[4]. Second, forest regrowth usually has higher diversity than old-growth, and little

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[3] In comparison, the systems surrounding farmers seem much simpler, although they too have non-linearities, and spatial patterns have a significant effect.

[4] The analysis in Dove (1983) was done by taking the income levels of the groups benefiting from the different methods as given; in dollar terms, wood management produced higher value.

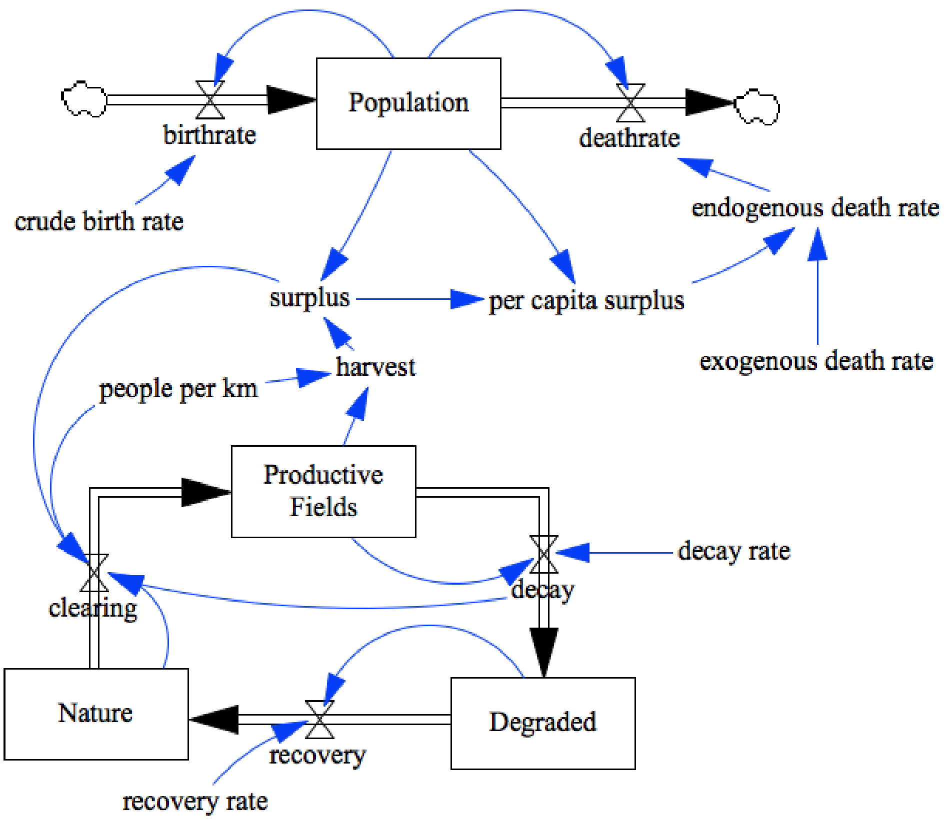

FIGURE 3. A system dynamical model of slash-and-burn agriculture. Description in the text.

danger of species loss (Chidumayo and Gumbo, 2010). The sister paper I am writing this semester looks at optimal harvesting patterns for slash-and-burn agriculture.

Below I explore a simple system dynamics model of slash-and-burn agriculture, for the purpose of understanding how future scenarios might affect the fate of slash-and-burn farmers.[5]

The lower loop of stocks in figure 3 cycles area between Nature, Productive Fields, and Degraded land. Nature is turned into productive fields by clearing, which is done at a rate equal to the decay rate of the productive fields, plus any surplus gap. In the base case, productive fields decay at a rate of 20% per year, but regenerate at only 2% per year (so that about 10x more land needs to be under regeneration than cultivation). The crude birth rate is constant, but the death rate is calculated by adding to an exogenous death rate a famine die-off for a fraction of any unsustainable population due to any food shortages.

The effect of different scenarios are simulated with reference to a hypothetical situation. The system dynamics are completely determined, as a consequence of parameters, but the parameters are determined by the scenario. Hypothetically, a population enters a pristine

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[5] The collapse of the Mayan civilization may be a useful mirror for the consequences of using technology to maintain systems of environmental exploitation in the tropics and under climate change. Their actions produced new feedback loops, some of which were both driven by the need to maintain human development, and whose problems were caused by that same development.

forest with characteristics typical of 2050 under each of the different scenarios, and the dynamics play out. A better analysis would recognize that the different scenarios entail changes to the system structure itself (for example, the influence of market forces under Global Orchestration, permanent environmental damage under Order from Strength, and localized technologies under Adaptive Mosaic, and global controls under TechnoGarden).

Below are the scenario values (in **bold**) and resulting system parameters (*italicized*).

Scenario	**RS**	**TT**	**MC**	CBR	EDR	Y/km^2	RR	DR
Current Parameters	0	0	165	35/1000	20/1000	230	.02	.2
Global Orchestration	-55%	2	65	20/1000	10/1000	400	.009	.2
Order from Strength	-100%	1	180	37/1000	22/1000	325	0	.2
Adaptive Mosaic	68%	3	145	32/1000	18/1000	460	.034	.2
TechnoGarden	55%	4	105	26/1000	14/1000	560	.031	.2

Descriptions of the columns below. The results of the model runs are in figures 4 and 5.

Regulating Services (RS): from figure S10 of Bennett et al. (2005a)

Tropical Technology (TT): rank from least (1) to most (4) from the "investment in learning about the environment" and "emphasis on development of environmental technology" rows of table 5.1 in Bennett et al. (2005b)

Malnourished Children (MC): in millions in 2050, from figure S5 of Bennett et al. (2005a)

Crude Birth Rate (CBR): Births per person per year: $CBR = 1.5 * EDR + 5/1000$

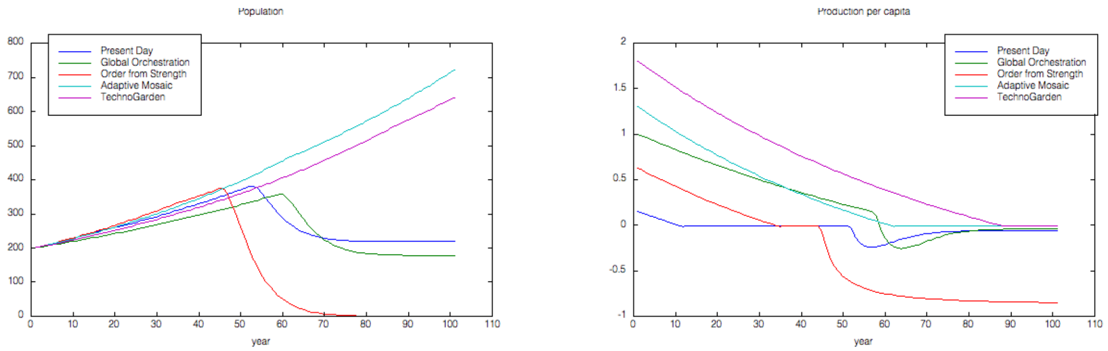
Exogenous Death Rate (EDR): Deaths per person per year: $EDR = (MC + 35)/10$

Productivity (Y/km^2): Number of people who can be supported on one km^2 of land: $Y/km^2 = 230 * \sqrt{TT + 1}$

Recovery Rate (RR): Rate at which degraded forest recovers (as a portion of all degraded forest): $RR = .02(1 + RS)$

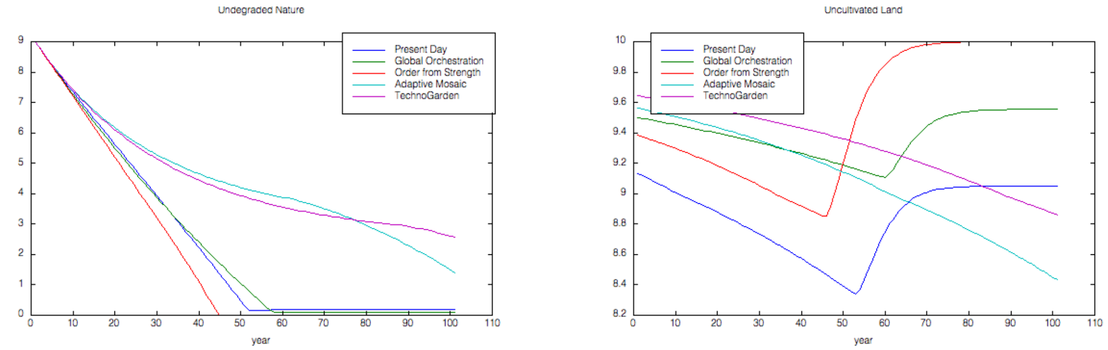
Decay Rate (DR): Rate at which productive fields decay, assumed not to change amongst scenarios: $DR = .2$

The model shows the highest population and the highest production per capita (a measure of wealth) under the Adaptive Mosaic and TechnoGarden scenarios. Under Order from Strength, the population dies out. All four scenarios have higher amounts of total uncultivated land than under present day parameters. While Global Orchestration has the slowest decline in total uncultivated land, it has a much earlier "stability point" (around year 60) than the Adaptive Mosaic or TechnoGarden.


Population

Production per capita

Figure 4. Population and Per capita production.


Undegraded Nature

Uncultivated Land

Figure 5. Undegraded nature and total uncultivated land.

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