OPTIMAL SLASHING-AND-BURNING

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Agriculture is one of the most pressing contexts for 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).

These issues are of particular concern in the tropics. Human need there is the greatest of any latitudinal zone (Bloom et al., 1998). Potential for biodiversity loss is much larger than other regions (Wiens and Donoghue, 2004). A leading cause of deforestation is small-holder farming (Southgate, 1990), but the huge number of small-holder farmers and weak governments make enacting policy difficult (e.g. 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 (WorldBank, 2007, Harwood, 1996) 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 behavior changes in resource-strapped areas.

In this paper, I investigate optimal slash-and-burn practices.[1] Worldwide, 240 to 300 million sustenance farmers practice slash-and-burn agriculture (Dove, 1983), on an estimated 12.4 million km^2 (see figure 1. Over 1.5 million km^2 of this is unsustainable harvested, resulting in deforestation and its many associated ills. The existing literature only addresses this problem tangentially, and the full complexity of the problem is only clear within a spatially explicit

[1] "Slash-and-burn" agriculture is also known as fire-fallow or swidden agriculture, or shifting cultivation. I use the term "slash-and-burn", but intend no negative connotations.

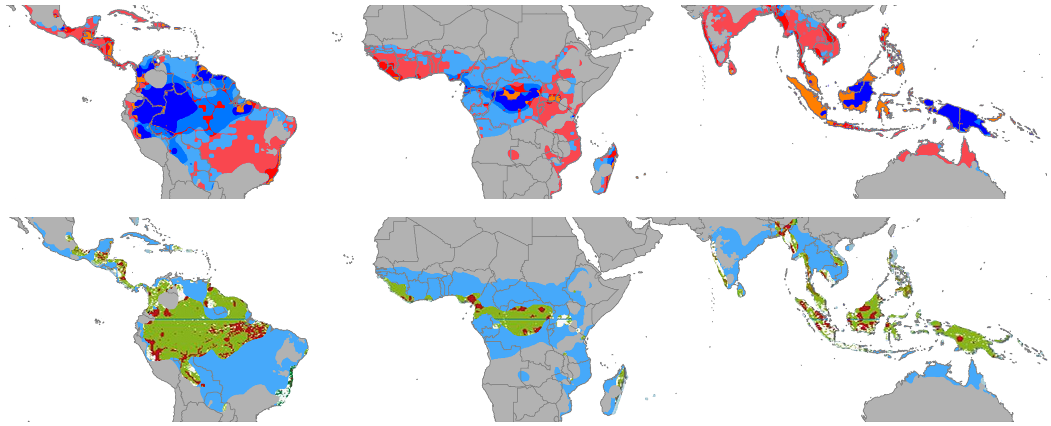

FIGURE 1. Attempts to identify slash-and-burn regions. (1) The top map shows in shades of blue regions of tropical climate (Köppen climate zones Af, Am, and Aw) where cropland is present but less than 10% of land area, according to Ramankutty and Foley (1998). This is the range at which slash-and-burn 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.

context. This paper also acts as an opportunity to experiment with the use of economic optimality in a spatial context.

Four models are explored: a behavioral system dynamics model, an aggregate biomass-fertilizing model, a 1-D biomass-fertilizing model, and a 2-D transportation network model.

1. Existing Literature

Existing economic analyses of slash-and-burn farming tend to focus on household decision-making (Barrett, 1999, Vosti and Witcover, 1996), effects on deforestation (Southgate, 1990, Gehring et al., 2005), and carbon dynamics (Kotto-Same et al., 1997, Uhl, 1987). Theoretical attempts to find improvements to agricultural practices have used systems approaches instead (Harwood, 1996, Ikerd, 1993)

Trade-offs exist between land use options that can only be fully explored with spatially explicit models, such as InVEST. Many current use patterns are simultaneously suboptimal on economic and ecological grounds (e.g. Polasky et al., 2008). Two points suggest that similar win-win opportunities exist for these 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)[2]. Second, forest regrowth usually has higher diversity than old-growth, and sustainable slash-and-burn cultivation causes little danger of species loss (Chidumayo and Gumbo, 2010). Surveys have revealed that technical efficiency amongst slash-and-burn farmers is around 75% (Binam et al., 2004).[3]

Chomitz and Gray (1996) performed an empirical study of the effects of roads on development and deforestation, finding that areas typical of slash-and-burn farmers are not much helped economically and harmed environmentally. This research drives to find a better approach, which might find benefits where current practices do not.

Intuitively, the Faustmann model of optimal forest rotation can be used to analyze slash-and-burn agriculture. It sets the proper time for leaving a region fallow, assuming that cultivation needs to move all at once, and that there is a direct correlation between forest biomass and farm productivity. I offer results from the Faustmann model in the comparison below.

2. Behavioral Model

I consider a conceptual, system dynamics model. It is aggregated, rather than spatially distributed, and applies behavioral, rather than optimal, decision-making. See figure 2.

The lower loop of stocks in figure 2 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 basic set of

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

[3]Barrett (1999) mention that "shifting cultivation based on long fallow periods can be an ecologically sustainable and economically optimal practice in tropical forests" and reference Peters and Neuenschwander (1988). However, Peters and Neuenschwander use the word "optimal" only once in their book (that increases in nutrients produce small production increases, "suggesting that an optimal nutrient level exists"). The book is not available online (except for searches), so I pursued it no further for the purposes of this paper.

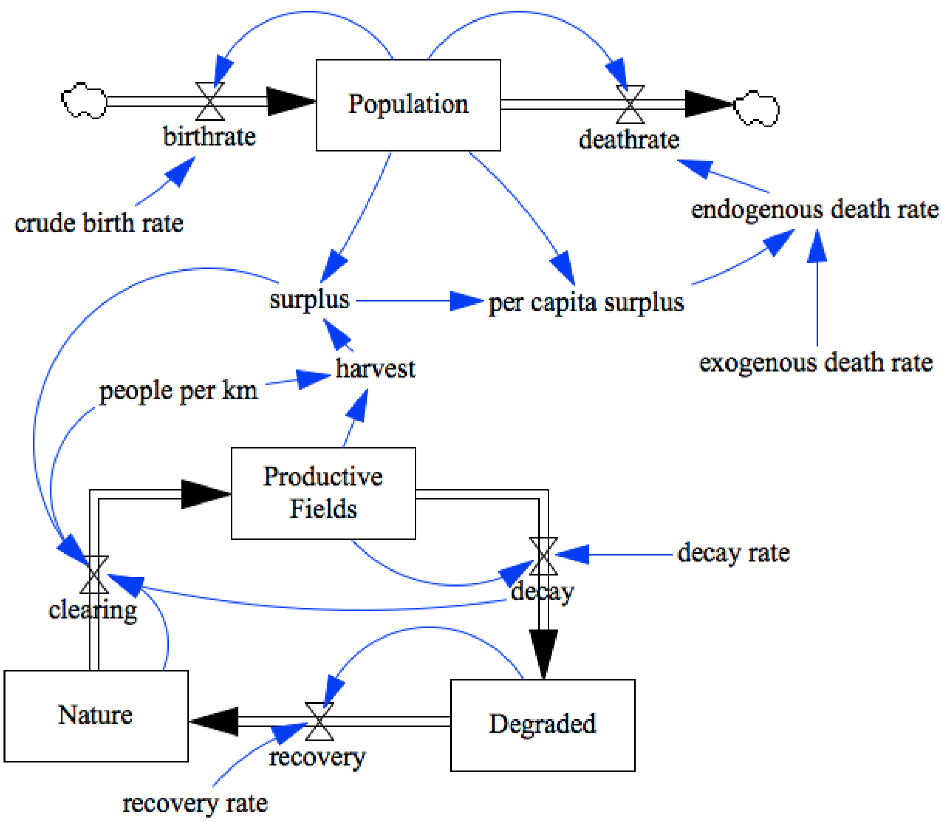

FIGURE 2. A system dynamical model of slash-and-burn agriculture. Land cycles between extractive and regenerative uses. The population grows along Malthusian grounds and increases harvest land accordingly.

parameters, 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, typical of real systems). 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 food shortages. This induces Malthusian growth.

A sample run is displayed in figure 3. Initially, of a 100 km^2 region, a population cultivates 2 km^2. This produces more than the population needs, so population grows until the surplus is taken up, after which clearing increases to counteract the insufficient harvests. Clearing and population growth continues, until all pristine nature is exhausted. At this point, there is a famine crisis, and many people die. However, after this, the population attains a sustainable level. For these parameters, that level is approximately 9 km^2 (or 1/11th of the forest). Each

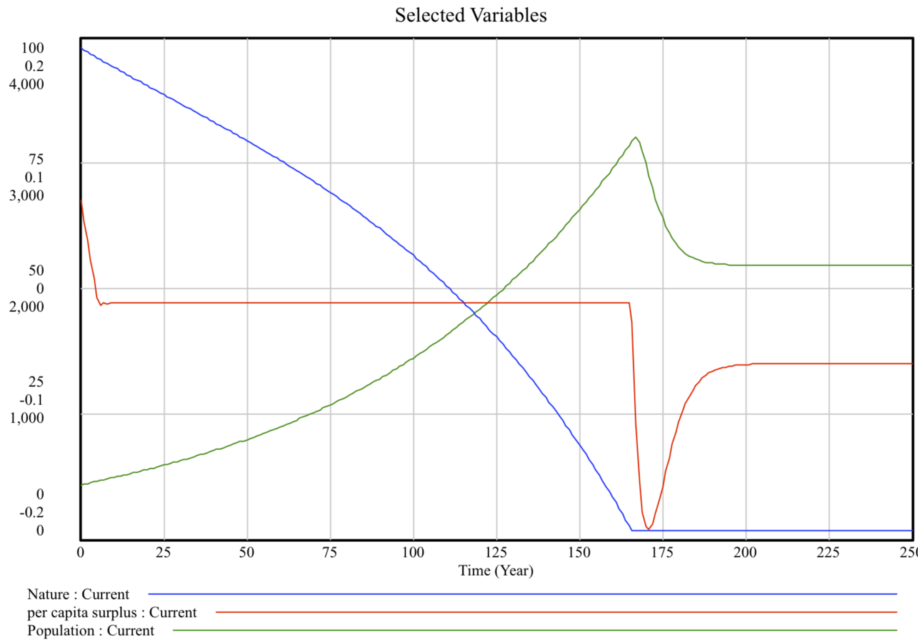

Figure 3. A system dynamical model of slash-and-burn agriculture. Description in the text.

year, 1.8 km^2 (or 1/5th of the productive areas) are cleared, to offset the same amount that degrades.[4]

3. Optimal Aggregate Harvesting

The optimal resource dynamics of the system model are analyzed in a framework where nature produces biomass, and slashing-and-burning harvests it to add fertility to fields.

Biomass is a renewable resource, which naturally grows according to a growth function $F(b, 1-p)$, where b is the current biomass, p is the agricultural land, and both total area and maximum biomass are normalized to 1, so that $1-p$ is the carrying capacity. By slash-and-burning a portion of the unfarmed land, the aggregate biomass decreases and the food production fertility increases, while the area left to nature decreases and the area for food production increases. Simultaneously, area can be released to nature to regrow biomass.

[4]I have also tried parameters derived from the four scenarios in the Millennium Ecosystem Assessment, but with the exception of the Order from Strength parameters, in which the population dies out, the dynamics are similar.

Within this model, we can define two state variables: $b(t)$, the total stock of biomass; and $f(t)$, the stock of field fertility; and two control variables: $p(t)$, the area under agricultural use; and $r(t)$, the instantaneous rate at which new area is slashed-and-burned. Land is released to regenerate at a rate $r(t) - \frac{dp}{dt}$.[5] Note that one optimality condition is that the amount of untouched forest, if we were to include it in the model, is 0.

The fundamental equations for the evolution of state are,

$$\frac{db}{dt} = F(b, 1-p) - rb, \text{ and}$$
$$\frac{df}{dt} = rb - \beta f$$

Here, β is the fertility decay rate.

First, consider the steady-state of the case without discounting. The problem is to find the maximum sustainable yield, $\max_{p,r} pf$.

$$\frac{df}{dt} = 0 \implies f = \frac{rb}{\beta}$$
$$\frac{db}{dt} = 0 \implies F(b, 1-p) = rb$$
$$\implies \max_{p,r} \frac{p}{\beta} F(b, 1-p)$$

In this formulation, r and p are independent variables, and any level of biomass, $b < 1 - p$, can be maintained by selecting the appropriate rate r. At a given level of p, the maximum level of b results in the maximum level of f. So, the maximization problem may be done in two steps: $\max_{p,f} \frac{p}{\beta} F(b, 1-p) = \max_p \frac{p}{\beta} \max_b F(b, 1-p)$,

For the logistic growth function, $F(b, 1-p) = \alpha b \left(1 - \frac{b}{1-p}\right)$, and $\arg\max_b F(b, 1-p) = \frac{1-p}{2} \implies \max_b F(b, 1-p) = \alpha \frac{1-p}{4}$.

$$\max_{p,r} pf = \max_p \frac{\alpha}{4\beta} p(1-p)$$

[5]This is only one possible collection of variables, but it is the easiest to analyze. I have also considered letting $p(t)$ be a state variable, under two control variables $s(t)$ (slashing rate) and $r(t)$ (releasing rate).

This is maximized at $p = \frac{1}{2}$, irrespective of the growth rate, α, or fertility decay rate, β. This is a very powerful result: given logistic growth, the maximum sustainable yield for biomass fertilizing agriculture is where only half of the region is under agriculture.

For the discounting case, the problem is as follows:

$$\max_{p(t),r(t)} e^{-\delta t} \left(p(t)f(t) - c_p(p(t)) - c_r(r(t))\right) dt$$

under the state evolution equations above. Costs are necessary, $c_p(\cdot)$ for maintaining agricultural land and $c_r(\cdot)$ for slash-and-burning new forest, to find an interior solution. The Hamiltonian is,

$$H = e^{-\delta t} \left(pf - c_p(p) - c_r(r)\right) + \lambda_1 \left(F(b, 1-p) - rb\right) + \lambda_2 \left(rb - \beta f\right)$$

Assume that $c_p(p) = c_p p$ and $c_r(r) = c_r r$. Then the FOCs are,

$$\begin{aligned}
\frac{\partial H}{\partial p} &= 0 = e^{-\delta t}(f - c_p) - \lambda_1 F_K(b, 1-p) \\
\frac{\partial H}{\partial r} &= 0 = e^{-\delta t} c_r - \lambda_1 b + \lambda_2 b \\
\frac{\partial H}{\partial b} &= \dot{\lambda_1} = \lambda_1 (F_b(b, 1-p) - r) + \lambda_2 r \\
\frac{\partial H}{\partial f} &= \dot{\lambda_2} = e^{-\delta t} p - \beta \lambda_2
\end{aligned}$$

Where F_b is the partial of F with respect to biomass, and F_K is the partial with respect to carrying capacity.

In the steady-state, it can be shown that,

$$\begin{aligned}
\lambda_1(t) &= \frac{pr}{(\delta - \beta)(F_b(b, 1-p) - r + \delta)} e^{-\delta t} \\
\lambda_2(t) &= \frac{p}{\beta - \delta} e^{-\delta t}
\end{aligned}$$

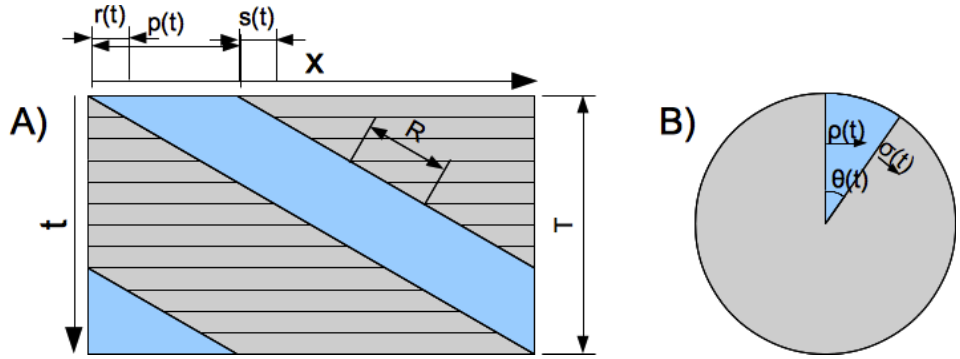

FIGURE 4. Diagram for the 1-D model. (A) shows the shifting of agricultural area through time. For this model, an angular framework, (B), is easier to analyze.

and

$$f - c_p = \frac{prF_K(b, 1-p)}{(\delta - \beta)(F_b(b, 1-p) - r + \delta)}$$
$$c_r = \frac{pb}{\delta - \beta}\left(\frac{r}{(F_b(b, 1-p) - r + \delta)} + 1\right)$$

These equations have a closed-form solution for the logistic equation, but it is too long to write here. I evaluate it for parameter values below.

Finally, consider a proper 1-D model, in figure 4. In this model, every point has its own evolution in time of biomass growth (when uncultivated), and fertility decay. Slashing-and-burning naturally moves in a circle, progressively harvesting the areas that have been left to regenerate longest. I use Greek letters to denote angular variables (in addition to the constants used before). In this case, as with the Faustmann model, after cultivation for the logistic function to provide new growth, an initial biomass is needed when the land is released. I call this b_0.

The new optimization problem, in the reference frame of the cultivated area, is

$$\max_{\rho(t),\theta(t)} \int_0^\infty \left[\int_0^{\theta(t)} f(\phi, t)d\phi - c_p\frac{\theta(t)}{2\pi} - c_r\frac{\rho(t)}{2\pi}\right] e^{-\delta t}dt$$

Here, $\theta(t)$ is the size of agricultural land, in angular coordinates. $\rho(t)$ is the rate of new slashing-and-burning.

Analyzing this model in full is difficult, but the undiscounted steady-state is not too onerous. In the steady-state, the fertility gradient within the cultivated area is constant with respect to time, in the reference frame of that area. On the leading edge, it starts with some fertility, f_0. With the cultivation area rotating at a rate ρ, a point to the right of the leading edge, at an angle ϕ, has been under cultivation for $t = \frac{\phi}{\rho}$. So, the function for fertility over the cultivated area is,

$$f(\theta) = f_0 e^{-\beta \frac{\phi}{\rho}}$$

and the agricultural production (the inside integral of the optimization problem) is,

$$\int_0^\theta f_0 e^{-\beta \frac{\phi}{\rho}} = f_0 \frac{\rho}{\beta}\left(1 - e^{-\beta \frac{\theta}{\rho}}\right)$$

The initial fertility, f_0, depends on the growth model and the time between cultivation. That time is given by $\rho T = 2\pi - \theta \implies T = \frac{2\pi - \theta}{\rho}$. Then, for the logistic growth function (which has a closed-form expression),

$$\begin{aligned} b(t) =& \frac{(1 - \frac{\theta}{2\pi})b_0}{(1 - \frac{\theta}{2\pi} - b_0)e^{-\alpha t} + b_0} \\ \implies f_0 = b(T) =& \frac{(1 - \frac{\theta}{2\pi})b_0}{(1 - \frac{\theta}{2\pi} - b_0)e^{-\alpha \frac{2\pi - \theta}{\rho}} + b_0} \end{aligned}$$

Substituting in and evaluating the integral over time, we have

$$\max_{\rho,\theta}\left[\left[\frac{(1 - \frac{\theta}{2\pi})b_0}{(1 - \frac{\theta}{2\pi} - b_0)e^{-\alpha \frac{2\pi - \theta}{\rho}} + b_0}\right]\frac{\rho}{\beta}\left(1 - e^{-\beta \frac{\theta}{\rho}}\right) - c_p \frac{\theta}{2\pi} - c_r \frac{\rho}{2\pi}\right]$$

This has no closed-form solution. See figure 5 for the contours of this value function under the parameters compared below.

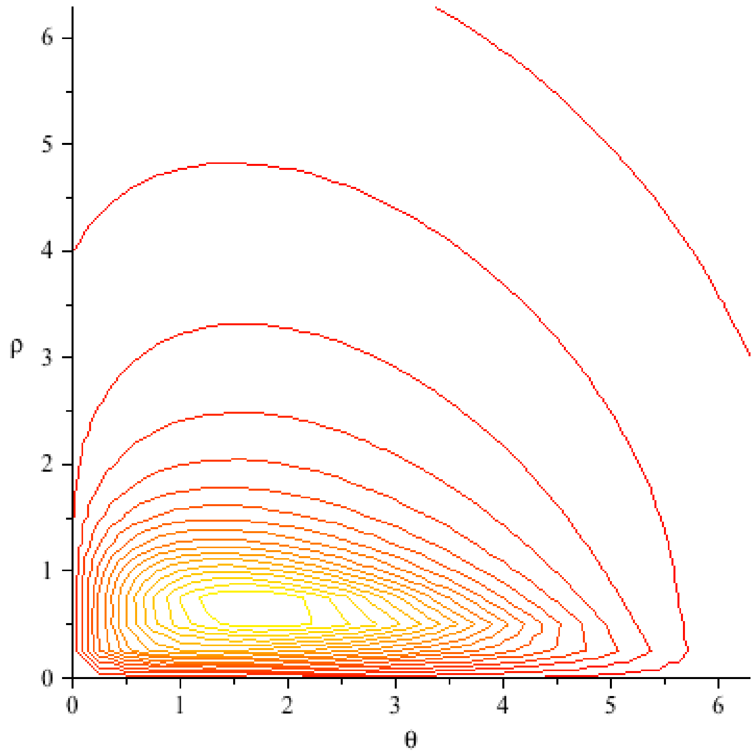

FIGURE 5. Contours for the case study parameters. The maximum is at $\theta = 1.7354$ and $\rho = 0.6494$.

As a case study, we compare Faustmann results to the optimal cultivation models, for a logistic growth function, $\alpha = 1$, $\delta = .03$, $\beta = .4$, $c_{Faustmann} = .1 = c_r = c_p$. The results are below, and shown graphically in time in figure 6.

Model	δ	profit / yr	avg. biomass	avg. ag. area	harvest rate
Faustmann	.03	0.0882	0.4179	0.0909	0.0909
Aggregate	.03	0.1464	0.2708	0.3879	0.5576
Aggregate	0	0.3125	.25	.5	.5
1-D Model	0	0.6744	0.2877	0.2762	0.1034

The Faustmann model has a harvesting every 11 years, while the aggregate model has a higher, continuous harvesting. The profit from the Faustmann formula (in dimensionless terms) is lower than the aggregate model profit. It's not clear how closely these models can be compared however.

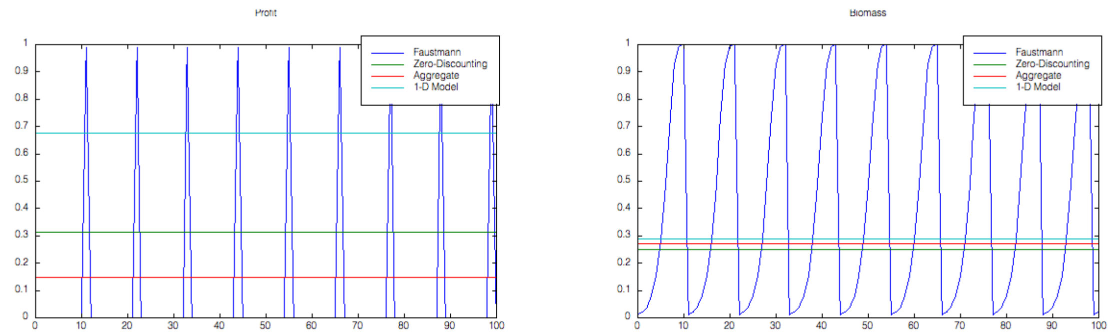

Figure 6. Comparison of various harvesting methods.

The steady-state 1-D model shows both higher profit and higher biomass than the aggregate model. This points to the need for spatially explicit analysis in resource economics.

4. Optimal Transportation Networks

In a 2-D context, transportation becomes an important issue. If every location is equally accessible, the problem is identical to the aggregate problem, and if cultivation can move anywhere without serving outside needs, it is equivalent to the 1-D problem. One implementation of transportation relations is a static transportation network, which decreases the costs associated with harvesting a region. The optimal structure of that network is, in some sense, the optimal steady-state of the 2-D spatially distributed model.

Optimal transportation networks have been copiously studied, but with very different assumption. First, they are typically taken to be networks between nodes, rather than networks within "rural regions" (regions where all land can be traversed and is of interest). Second, they are general solved by means of randomized methods, such simulated annealing (Carlson, 1977). This is necessary because the total breadth of options is too great. However, simulated annealing and other numerical methods often find local optima rather than the global optimum. Below I use dynamic programming, which is provably optimal.

The general economic problem is to construct a transportation graph over a region, rooted in one corner of the region, which minimizes the integral of a cost over the region, where the cost is a function of the distance from any given point to its nearest line. Natural constraints

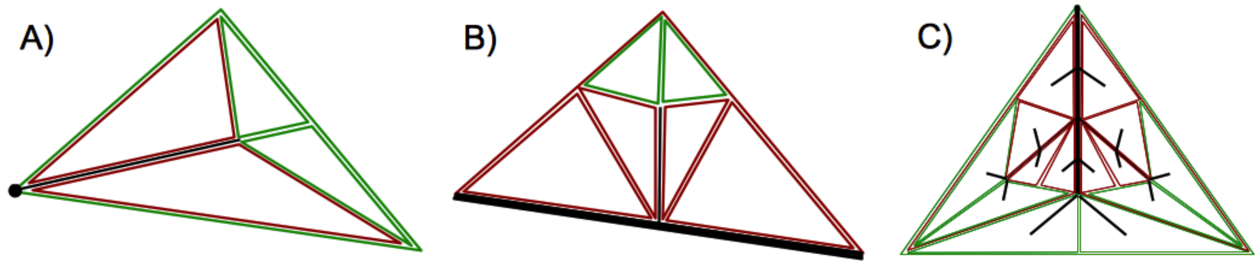

FIGURE 7. A and B show the two situations that are encountered in the optimal control problem. In A, a corner point is connected. The optimal transportation transportation edge is taken to be a line segment that bisects the corner's angle, for an optimal distance s. The space is then subdivided into two more A-type triangles (green), and two B-type triangles (red). In B, one edge is connected. The optimal transportation edge is taken to be a line segment bisecting the connected line toward the opposite corner, for a distance s. The triangle is subdivided into two A-type triangles (green), and four B-type triangles (red). C shows a possible solution to the equilateral triangle problem, using the same color scheme.

can be placed on the size of the transportation graph by (1) imposing a cost on the length of the graph (e.g., for maintenance, or to reflect opportunity costs for land use), or (2) including utility that is a function of the size of regions not divided by transportation edges (e.g., to reflect property schemes or ecological needs).

To construct a computationally feasible optimal control problem, I make a few simplifications. First, instead of applying either natural constraint above, I use a kind of dual to the cost minimization problem: the total length of the graph is set. Second, rather than allowing any graph structure, I limit the search to trees. Third, I take the full region to be a triangle, and the search proceeds by subdividing the triangle into smaller triangles. The optimal tree within each triangle is taken to be a function only of the properties of the triangle and the total length allocated to it. Figure 7 lays out this method.

There are two optimal control transforms, two optimal value functions, and two utility functions. $V(\theta, a, b, s)$ is the value function for a triangle connected at one corner with an optimal transportation network inside. $W(\theta, a, b, s)$ is the value function for a triangle connected along one edge.

$$u_A(a,b,c) = \iint u(\sqrt{x^2+y^2})dxdy \text{ (aligning corner at 0, 0)}$$
$$u_B(a,b,c) = \iint u(y)dxdy \text{ (aligning side as base)}$$
$$\mathcal{T}_{\mathcal{A}}V(a,b,c,s) = \max_{s_i} u_A(a,b,c) - v(s_0) + \beta\left(V(\cdot_1) + V(\cdot_2) + W(\cdot_3) + W(\cdot_4)\right)$$
$$\mathcal{T}_{\mathcal{B}}W(a,b,c,s) = \max_{s_i} u_B(a,b,c) - v(s_0) + \beta\left(V(\cdot_1) + V(\cdot_2) + W(\cdot_3) + W(\cdot_4) + W(\cdot_5) + W(\cdot_6)\right)$$

Here, $u(d)$ is the utility of agricultural land a distance d from the closest edge of the transportation network. $v(s)$ is a cost for the transportation path. These equations satisfy both the monotonicity and discounting criteria.

In the equations for the transforms, s is divided into an optimal collection, s_i, where $i \in [0,4]$ for $\mathcal{T}_{\mathcal{A}}$ and $i \in [0,6]$ for $\mathcal{T}_{\mathcal{B}}$. $\sum_{i=0}^{N} s_i = s$. The parameters of the value functions above are shown as $(\cdot_i)$ which includes the parameters for the sub-triangle and the appropriate s_i.

This method is not implemented, but seems like a natural extension of the resource-usage problems.

5. Empirical Diagnostics

There are a wide range of reasons why observed slash-and-burn patterns might not follow these optimal analyses, but two stand out. Population pressure may drive resource users to over-harvest, out of necessity. Similarly, other factors depressing the population or any environmental policies could result in under-harvesting. Second, modern agricultural inputs will entirely change the needs of the model. Other sources of difference, like other land uses and property rights, should place spatial restrictions on the dynamics, but not change them within their realms.

For this reason, however, these model results can provide interesting large-scale diagnostics. The models posit relationships between rates of movement and agriculture size. These can be measured using image processing of satellite data, and thereby improve estimates of the amount of land under slash-and-burn cultivation. Image processing can also be used to identify the existing structures of transportation networks, widely recognized as encroaching into the Amazon and other forests. By identifying informative statistics, like the clustering coefficient, one could identify regions of suboptimal transportation, which might result in excessive destruction.

6. Future Work

The models used in this paper on the edge of analytical methods, but are far from accurate descriptions of the relevant dynamics. Evidence suggests that secondary-growth forests have very different compositions than old-growth, and that this can have direct impacts on the productivity of slash-and-burn agriculture (Gehring et al., 2005). Reductions in fallow periods not only decrease biomass fertilization, but increase weeding requirements (Roder, 1997). The next step in this work is to work toward a synthesis model. By taking the transportation network as given, more of these intricacies can be incorporated by looking at perturbations of the steady-state.

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