Bio-economic sustainability of cellulosic biofuel production on marginal lands

Andrew Paul Gutierrez¹,²,* and Luigi Ponti²,³

¹ Division of Ecosystem Science, University of California, Berkeley, CA, USA 94720
email: carpediem@nature.berkeley.edu
tel: 510 642 9186

² Center for the Analysis of Sustainable Agricultural Systems (CASASglobal)
37 Arlington Ave., Kensington, CA, USA 94707.

³ ENEA, Dipartimento BAS, Gruppo “Lotta alla Desertificazione”, S.P. Anguillarese 301,
00123 S. Maria di Galeria (Roma), Italy
email: (Luigi Ponti) quartese@gmail.com
tel: (+39) 338 9844 677

* To whom correspondence should be addressed.

Key words: bioeconomics | second generation biofuels | physiologically based models |
resilience| sustainability|
SUMMARY

Marginal lands (ML) are defined as being unfit for the economic cultivation of food crops, and here their conversion for industrial production of cellulosic biofuel is examined from the point of view of system stability, resilience, and eco-social sustainability. Tritrophic physiologically based demographic models (PBM) are used to examine the stability properties of ML ecosystem before and after conversion (Gutierrez, Mills, Schreiber, & Ellis, 1994). The PBM are embedded in the objective function of the bio-economic model that maximizes the utility of consumption and has the dynamics of the resource to be managed (MLs) and the manger as dynamic constraints (Regev, Gutierrez, Schreiber, & Zilberman, 1998; Gutierrez & Regev, 2005). The bio-economic model is used to examine the effects of increased conversion efficiency ($\theta$), input costs ($v$), risk ($\delta$), and levels of base resources and inputs ($R$) on the competitive ($x_C$) and societal optimal ($x^*$) solutions for biomass production and on the marginal price of biomass ($\lambda^*$).

The diversified North American prairie grass system harvested for biomass (Tilman, Hill, & Lehman, 2006) and its industrialization for maximum biomass production using biotechnology and nutrient inputs is used as a foil. In the absence of pests and diseases, both systems are stable with the latter being artificially maintained. However, if pests and diseases become severe, the farmer/biofuel producer becomes the intermediate trophic level and the system becomes increasingly unstable.

In bioeconomic terms, factors that increase risk ($\delta$) decrease the marginal price of the biomass ($\lambda^*$) and decrease the optimal level of biomass production ($x^*$), but the competitive level of biomass production ($x_C$) remains unchanged. However, increasing efficiency of biomass production ($\theta$) increases the marginal price, but decreases $x^*$ and $x_C$ suggesting an increasing trend for over exploitation. The interaction of increasing risk and efficiency increases exploitation possibly to the point of farmer bankruptcy.
The question of land abandonment after biofuel production ceases could lead to permanent land degradation below initial levels that prohibit the establishment of the original flora and fauna.

**INTRODUCTION**

Many technologists operate as *cornucopians* (*sensu* Simon & Kahn, 1984; Beckerman, 1995) assuming that technology has an infinite capacity for solving problems in food production, and now for increasingly renewable sources of energy using biofuels: ethanol and bio-diesel. They posit that biofuels are a renewable source of energy because it can be produced from plant starch or cellulose biomass, often ignoring environmental and social costs and the real possibility that it may increase green house gases (GHG). They point to the strides made by oil poor Brazil that during its deep 1970-1990’s financial crisis stimulated ethanol production based on sugar cane to help solve its energy needs and reduce it balance of payments deficits. Currently, corn, soybean, palm oil and other crops are being used in various parts of the world for biofuel production with second generation cellulosic ethanol production under development. It has been proposed that *marginal lands* (ML), defined as land unfit for the economic cultivation of food crops, could be used for biomass production using species such as perennial North American prairie grasses (*e.g.* switchgrass, *Panicum virgatum*), Asian grass (*Miscanthus sinensis*), hybrid poplar trees, the medicinal plant *Jatropha curcas* and others. The underlying assumption is that their conversion for biofuel production would decouple biofuel production from agriculture lands and crops devoted to food production, and also reduce green house gas (GHG).

The use of biofuel production to solve the energy crisis globally has been questioned on ecological (Chapin III et al., 2000; Searchinger et al., 2008), energetic (Patzek, 2006) and social grounds because it increases global hunger (Pimentel & Patzek, 2005; Ford Runge & Senauer, 2007), as well as on technological grounds that posit future breakthroughs to solve current problems in ligno-cellulosic based biofuel production. A series of letter edited by Kavanagh (2006) reviews many of the arguments, and what is clear from them is that the links between research and development and the policy environment concerning biofuel production are exceedingly poor with the requisite
What is also apparent is that analysis of biofuel technologies are often addressed piece-meal rather than holistically, making it difficult to show the link of the ongoing political and profit motivated R&D pushing the biofuel technology as a sustainable option and the knowledge of environmental sustainability at any spatial dimension. Robertson et al. (2008) outline many of the pitfalls and call for a systems approach to implementing the technology. A major pitfall is the “carbon debt” that may be incurred in implementing the technology. 

The carbon debt is defined as the amount of CO\textsubscript{2} released during the first 50 years after land conversion for biofuel production, a debt that can be repaid only if the production and combustion of the biofuels have net GHG emissions less than the life-cycle emissions of the fossil fuels they displace (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). They posit that the repayment time would be zero years for diversified North American prairie grassland to as much as 423 years for SE Asian peat land rainforests converted to palm bio-diesel. Field, Campbell, & Lobell (2008) suggest that abandoned crop and pasture lands are a huge resource that would circumvent some of these problems as much of the carbon debt has already accrued. In our discussion, abandoned lands will be included under the ambit of MLs.

Tilman et al. (2006) showed diversified North American prairie grasslands (MLs) with switch grass as a component yielded slightly less net biomass ethanol on with minimal inputs than did ethanol produced using high input corn grain from agricultural lands (17.8 vs. 18.9 GJ h\textsuperscript{-1}). Their study showed that biomass production and carbon sequestration in diversified grasslands increased asymptotically with time due to the benefits of nitrogen fixation but note that inputs of potassium would be required. The question of the depletion of other minerals and micronutrient was not addressed, but in private correspondence, Tilman estimates it would occur on the scale of 100 years. If correct this would be a win-win situation, but such sustainable system are rarely sustainable due to the incessant conflict between the economy of nature and the economy of humans (Regev et al., 1998; Gutierrez & Regev, 2005).
For example, what happens if such systems are industrialized for maximum biomass production. Searchinger et al. (2008) showed that ethanol produced from corn doubles GHG emissions over 30 years, while growing monocultures of switch grass on corn land increased emissions 50%. In general, a larger positive carbon debt is expected to occur if biofuel systems on MLs are industrialized using genetic improvement for plant development, chemical composition, tolerance to biotic and abiotic stresses and especially the use of inputs of nutrients to increase their environmental range and yield. According to Koonin (2006), biofuel plant enhancement using a combination of modern breeding and transgenic techniques could achieve results “… greater than those of the Green Revolution in food crops, and in far less time.” But are industrialized ML systems sustainable and what is the fate of such lands when they are abandoned?

**Sustainability and resilience** - Goodland (1995) proposed that renewable resource management requires ecological, economic, and social sustainability, and furthermore that sustainability can be achieved only by keeping the scale of the human economic system within the biophysical limits of the ecosystem. Holling (1978) defined *resilience* as the magnitude of disturbance a system can experience before it shifts into a different stability domain with different controls on system structure and function, and that failure to maintain desirable pathways and ecosystem states (Folke et al., 2002; Holling & Gunderson, 2002; Walker, Holling, Carpenter, & Kinzig, 2004) can have unexpected and often irreparable consequences. We note that the self-repairing capacity of ecosystems can no longer be assumed, as human development and exploitation of renewable resources often exceed system *resilience* capacity (Folke, 2006). Here we use these concepts to examine the diversion of ML for industrial biofuel production in a bio-economic framework.

**Bio-economic analysis**

Waltner-Toews et al. (2003) and Waltner-Toews (2004) posit that the dynamics of the renewable resource to be managed (e.g. MLs) and the resource manager (i.e. farmers/biofuel producer) must be included in the bio-economic analysis as done by
Regev et al. (1998). In this study, a general bio-economic model of renewable resource exploitation using a general physiologically based models (PBM s) of energy/mass flow in trophic chains including the economic consumer is used to examine the stability and bio-economic properties of natural and agro-industrialized grassland used for biofuel production (Gutierrez & Baumgärtner, 1984; Gutierrez et al., 1994; Regev et al., 1998). PBM s of the resource and the manager are included as dynamic constraints in the bio-economic objective function that maximizes the utility of consumption under different levels of risk (cf. Regev et al., 1998). The full suite of economic analogies for resource acquisition and allocation at all levels of natural and human economies, including the conflicting notions of biological and economic demand, consumption, and risk have been formulated and summarized in Gutierrez & Regev (2005) and table 1 and will be discussed in the text. These analogies are crucial to the development of our bio-economic analysis.

1 In economics, consumption is the hedonistic use of revenues in a way that does not contribute to firm growth and often leads to over-exploitation of natural resources by humans (Regev et al. 1998). In contrast, consumption in nature’s economy is the evolved use of energy in a manner that on average contributes to adaptedness but does not to individual growth (e.g. excess reproductive capacity in r-selected species and parental care in K-selected species; Gutierrez and Regev 2005).
The general predictions of the PBM are independent of time and place as they can be driven by local weather and edaphic factors (Gutierrez & Baumgärtner, 1984, 2007). The stability and other properties of PBM have been extensively documented (Gutierrez et al., 1994). Fig. 1a shows the energy flow and nutrient recycling in PBM of a natural ML ecosystem, while Fig. 1b shows the PBM representation of flows and agro-technical inputs (nutrients, water, pesticides, energy, etc) when the system is converted to industrial scale biofuel production. Respective inflow or outflow processes in all trophic levels including the economic one are characterized by the same process specific functions (see below). The harvested biomass is converted to biofuel sold to the ultimate consumer that in modern economies encourages high growing demand. The farmer and the biofuel producer can be viewed as the same from the point of view of the plant where the flow of biomass is multiplied by a constant that converts biomass/energy to monetary units, and is the transition between natural and human economies (fig. 1b). Note that nutrient recycling is greater in natural systems than in an industrial agricultural system.

In this paper, we examine possible consequences of using MLs for cellulosic biofuel production first from a biological point of view and then from an bioeconomic one. In

Table 1: Some analogies between natural and human economies

<table>
<thead>
<tr>
<th>Economy of Humans</th>
<th>Economy of Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>All global economies and interactions</td>
<td>Biosphere and its interactions</td>
</tr>
<tr>
<td>An economic system</td>
<td>An ecosystem</td>
</tr>
<tr>
<td>Industry</td>
<td>Species</td>
</tr>
<tr>
<td>Competing firms within an industry</td>
<td>Population</td>
</tr>
<tr>
<td>Firm</td>
<td>Individual</td>
</tr>
<tr>
<td>Firm decision rules</td>
<td>Genetics</td>
</tr>
<tr>
<td>Monetary units</td>
<td>Energy and biomass</td>
</tr>
<tr>
<td>Profit (maximize profit)</td>
<td>Reproduction (maximize fitness)</td>
</tr>
<tr>
<td>Firm stability</td>
<td>Adaptedness</td>
</tr>
<tr>
<td>Economic discount rate (δ)</td>
<td>Expected mortality rate (all causes)</td>
</tr>
<tr>
<td>Hedonistic consumption (C)</td>
<td>Energy for survival and enhanced adaptedness</td>
</tr>
</tbody>
</table>
natural systems, the posited objective is to maximize fitness and adaptedness in each
trophic level, while in an industrial context the goal is to maximize profit. This is the
inherent nature/human conflict (Gutierrez & Regev, 2005).

Fig. 1. Energy flow in natural (a.) and the same system converted to biomass/biofuel
production (b.). Note the agro-technical inputs in (b.) with the degree of nutrient
recycling indicated by the thickness of the lines (high, ——) and (low, ———) (cf. Gutierrez
& Curry, 1989; Regev et al., 1998). Net greenhouse gas (GHG) emissions are also
indicated.

**The Biological Point of View**

Mass (energy) flow in PBM consumer-resource dynamics (fig. 1) is modeled by Eqn.1
(Gutierrez & Baumgärtner, 1984; Gutierrez et al., 1994). The model has been used to
study energy allocation at the individual ($M_i=1$), population, meta-population and
regional levels (Gutierrez & Baumgärtner, 2007). Using the notation from Regev et al.
(1998), let $M_i (i = 1, 2, ..., n)$ denote the mass of the $i$th trophic level in a food chain, and
hence the dynamics of any trophic level is governed by the following equation of motion:
The parameters and components of the model are:

\[ M_i = \theta_i M_i D_i h(u_i) - v_i(D_i) M_i - M_{i+1} D_{i+1} h(u_{i+1}) \]  

(1)

\( D_i \) is the maximum per unit demand of the \( i \)th trophic level for resources trophic level \( i-1 \), and may be viewed as the sum of maximum outflows for each species including consumption \( (C) \),

\[ h(u_i) = \left(1 - \exp \left( -\frac{\alpha_i M_{i-1}}{D_i M_i} \right) \right) \]

is the proportions of the per unit demand \( D_i \) satisfied with \( D_i h_i(u) \) being the per capita resource acquisition by trophic level \( i \) from level \( i-1 \). \( 0 \leq h_i(u) < 1 \) is the supply-demand ratio,

\( \alpha_i \) is the proportion of level \( i-1 \) accessible to the \( i \)th level, and \( 1 - \alpha \) is a refuge of the resource,

\( \theta_i \) is the conversion rate of resource and includes wastage,

\( v_i(D_i) = vD \) is the cost rate per unit of consumer as a function of the demand rate that in poikilotherm species increases with temperature (i.e. the \( Q_{10} \) rule).

The function \( D_i h_i(u) \) is a ratio-dependent concave per unit functional response model that includes interspecific competition in the exponent and the possibility of several resource species having different \( \alpha \)'s and consumer preferences. The term \( D_i M_i \) is the maximum population demand and \( D_i M_i h_i(u) \leq \alpha_i M_{i-1} \) is the rate of resource depletion by all individuals of the \( i \)th level where \( \alpha_i \leq 1 \) sets the limits on the extraction by level \( i \) from resource level \( i-1 \). If \( \alpha_i \) is sufficiently small compared to the assimilation efficiency of the lower level \( (\alpha_i \leq \theta_{i-1} D_{i-1} - v_{i-1}(D_{i-1}) ) \), then the lower tropic level will survive any population size and demand rate of its consumer. We note that \( \alpha_i \) in industrial agriculture is exceedingly high.
The dynamics of biomass flow in the system (Eq. 2) include the soil biota ($M_0$), the vegetation ($M_1$), the herbivores ($M_2$), and the higher trophic levels ($M_3$) (fig. 1a) and may include human firms (see fig. 1b).

$$
\dot{M}_1 = \theta_1 M_1 D h(u_1) - v_1(D_1) M_1 - M_2 D h(u_2) \\
\dot{M}_2 = \theta_2 M_2 D h(u_2) - v_2(D_2) M_2 - M_3 D h(u_3) \\
\dot{M}_3 = \theta_3 M_3 D h(u_3) - v_3(D_3) M_3
$$

The parameters of the model can be estimated from field and/or laboratory data enabling the model to be used to analyze changes in interpretive dimensions in various regions of the world using weather and the dynamics of soil nutrients and water as forcing variables (Gutierrez & Baumgärtner, 2007). Below we analyze the stability properties of prairie grassland system on MLs, and the same system managed for industrial cellulosic biomass production. A similar analysis can be made of the use of wastes from forests and agricultural lands. We first analyze the stability properties of PBM as applied to a ML system.

**Stability of a prairie grassland system**

Undisturbed ecosystems are assumed to have solved the sustainable renewable resource management problem via selection including bottom-up effects (i.e. nitrogen fixation and micronutrient recycling) and top-down effects (i.e. herbivory-predation by higher trophic levels) (*sensu* Hairston, Smith, & Slobodkin, 1960; Fretwell, 1987). Extensive analysis of eqns. 1 and 2 has shown that two shapes of null isoclines arise for resources species that depend on the value of the apparency rate ($\alpha_{i-1}$) of the consumer species relative to the maximum per capita growth rate of the resource ($\theta_i D_i$) (see Gutierrez et al., 1994).
The inequalities for a natural perennial of a mixed grass system on MLs with low levels of nutrients and water ($M_0$) are expected to be $\alpha_2 > \theta_1D_1$ and $\alpha_3 > \theta_2D_2$ yielding a hump shaped null isocline for level $M_1$ (grass) and a C-shaped one for $M_2$ (herbivore) (Fig. 2a). A similar shaped isocline for $M_1$ was proposed by Noy-Meir (1975) for desert grasslands. The direction of the inequality $\alpha_2 > \theta_1D_1$ is due to the ability of herbivores to find and exploit the plants, while over exploitation is restricted by the action of higher trophic levels ($M_3$, natural enemies). The C-shaped $M_2$ null isocline intersects the $M_1$ isocline in two places producing both stable (●) and unstable (○) equilibrium. A similar analysis in the ($M_2, M_3$) phase space would yield a stable equilibrium the position of which depends on the level of nutrients ($M_0$). Specifically, equilibrium evolve at levels where the expected nutrient recycling rates, rainfall, soil pH and other abiotic factors are sufficient to meet the needs of the plants given higher trophic level effects.

In the ($M_2, M_3$) phase space, the inequality $\alpha_3 > \theta_2D_2$ yields the null isoclines shown in fig. 2b with a stable equilibrium (●). The resource species $M_1$ and $M_2$ in figs. 2a, b respectively achieve maximum population size at level $(\theta_iD_i)/v_i$ (see Gutierrez et al., 1994).
Fig. 2. Null isoclines for natural and managed grass land systems: (a) grass - herbivore phase space with low levels of nutrients \( M_0 \), (b) the herbivore – natural enemy phase space, and (c) the grass – farmer phase space with increasing inputs of nutrients \( M_0 \), and (d.) with increasing disease/pest damage \( M_3 \). (Symbol ● indicates stable equilibrium and ○ indicate unstable equilibrium.) The dotted arrow in fig. 2c indicates an increase in the \( M_1 \) null isocline due to inputs of nutrients and water.

Grassland converted to industrial biomass production – If farmers harvest an unimproved glass land system, a stable equilibrium occurs at point A (●, fig. 2c) only if farmers use sustainable practices that do not over exploit soil biota and the nutrients \( M_0 \). If soil nutrients are over exploited, the \( M_1 \) null isocline collapses toward the origin.

The transformation of natural grassland system, say using genetically modified (GM) switch grass to efficiently exploit soil nutrients and water with the goal of maximizing biomass production simplifies the system and makes the farmer/producer the top trophic level. GM plants “designed” to maximize yields with enhanced parameters values for \( \theta \), \( D \) and likely \( v \), (eqn. 1) allow the plants to grow faster and larger with increased dependence on external inputs of fertilizer and possibly water, and pesticides \( M_0 \), inputs that will increase production costs to farmers \( (v) \). In this ecologically simplified system,
farmer harvest capacity ($\alpha_z$) is considerably higher than the maximum growth rate of the plant ($\alpha_z > \theta_i D_i$) again resulting in a humped shaped plant isocline ($M_i$) with maximum potential yield at a much higher $\theta_i D_i / v_1$ in an artificially enriched environment (fig. 2c; point B). The farmer/biofuel producer $M_2$ isocline is sigmoid (fig. 2c, see Gutierrez et al. 1994). A stable equilibrium results at higher levels of biomass production with more/ bigger farmers (i.e. the shift from point $A$ to $B$) that can be sustained only so long as inputs are maintained ($M_0 \rightarrow M_{0,max}$), otherwise the trend will reverse direction (i.e. $B \rightarrow A$ or lower). The reduced rate of nutrient recycling is indicated by the dashed line in fig. 1b (vs. the solid heavy line in fig. 1a). Inputs increase costs $v_2$ that lowers the asymptote of the $M_2$ isocline (i.e. $(\theta_2 D_2) / v_2$) and reduces the number of farmers at equilibrium.

In seeking to maximize yield, farmers may use pesticides to control real or perceived pests that historically in other crops has led to ecological disruption and the scourges of pest resurgence, secondary pest outbreaks and pest resistance (e.g. van den Bosch, 1978). This could also occur due to unexpected consequences of biotechnology changes in plant physiology and growth (e.g. reduced lignin) or reduced genetic diversity. If diseases and pests become severe enough, farmers become the intermediate trophic level and the $M_2$ isocline becomes C-shaped having both a stable ($A$, ●) and an unstable ($B$, ○) equilibria (fig. 2d). As pest and disease levels increase (i.e. $M_3 \rightarrow \infty$), the C-shaped $M_2$ isocline moves rightwards and contracts causing the two equilibria to approach each other (fig. 2d). Because of increased pest damage, the $M_2$ isocline would also contract leftward, exacerbating the problem. These factors becomes increasingly important because perturbations away from the stable equilibrium increase the possibly of the system entering the unstable shaded region $C$ where economic collapse may occur. Perturbations leading to bankruptcy are more likely in a highly competitive environment where each farmer pursues self interest economic goals in a “pesticide addicted” environment (Regev, 1984), and as they spend money only to loose money leading to market failure (e.g. Gutierrez et al. 1974).
This raises the obvious question of ecological consequences when MLs are industrialized for cellulosic biofuel production and then abandoned for whatever reason. This problem is examined below from a bio-economic perspective that includes the renewable resource to be managed and the manager in the economic objective function.

**The Bioeconomic Point of View**

For clarity, eqn. 2 is simplified to represent the dynamics of \( x(= M_1) \) and \( y(= M_2) \) given a constant amount of soil nutrients \( R (= M_0) \) (Eqns. 3, 4 respectively) (cf. Regev et al., 1998).

\[
\frac{dx}{dt} \equiv x = G(R, x) - v_1(D)x - F(x, y) \quad (3)
\]

\[
\frac{dy}{dt} \equiv y = \theta \cdot F(x, y) - v_2(D_2)y \quad (4)
\]

From eqn. 2, \( G(R, x) = M_1 D_1 h_1(u) \) is the rate of \( R \) (nutrients) used by plants, \( F(x, y) = M_2 D_2 h_2(u) \) is the rate of \( x \) harvested by farmers (\( y \)), and \( v_1x \) and \( v_2y \) are the respiration and maintenance cost rates respectively defined as per unit of effort. The functions \( G(\cdot) \) and \( F(\cdot) \) satisfies the necessary concavity and positive marginal productivity conditions of economic models as both increase with resource levels, and decrease with intra-specific competition among consumers (i.e. the exponent \(-\alpha_iM_{i-1}/D_iM_i \) in \( h(u) \)) (eqn. 1) (Gutierrez et al., 1994). This reduced form of eqn. 2i-iii is included in the bio-economic objective function (eqn. 5).

**The bio-economic objective function** - The objective function for resource exploitation by all farmers of \( y \) seeking to maximize the present value utility of individual consumption (\( C \)) from the revenue stream is expressed as

\[
\max_{C_1, C_2} \int_0^\infty e^{-\delta t} yU(C) dt \quad (5)
\]
subject to the dynamics constraints of the managed crop of biomass $x$ (eqn. 3) and

farmers $y$ (eqn. 4), $e^{-\delta t}$ is the discount factor reflecting the level of risk ($\delta$), $t$ is time,

and the per unit demand ($D$) and consumption ($C$) rates of $y$ are control variables. $C$

(subscript ignored) is included via the monotonically increasing concave utility function

of individuals $U(C)$ that has properties $U'(C) > 0$, $U''(C) < 0$ and $U'(C) \to 0$

as $C \to \infty$. An extensive analysis of (5) is found in Regev et al. (1998) and hence is not

reproduced here.

By Pontryagin’s maximization principle, the maximization of eqn. 5 by all consumers

$y$ subject to population dynamics constraints of $x$ and $y$ (eqns 3, 4) is equivalent to the

maximization of the current value Hamiltonian (eqn. 6) (Fleming & Rishel, 1975)

$$H = U(C_t)y + \lambda_1(g - F) + \lambda_2[\theta F - (v_2D_2 + C_2)y],$$

where $\lambda_1$ and $\lambda_2$ are co-state or auxiliary variables associated with the dynamic

constraints $\dot{x}$ and $\dot{y}$. In particular, $\lambda_1$ is the Lagrange multiplier that represents the

marginal utility of income to $y$ from harvesting biomass $x$. The necessary conditions for

an optimal solution of (6) are met as described in Regev et al. (1998), $C^*(\delta)$ is an

increasing function of $C$, $\lambda_1 \leq U'(C^*)(\theta - v)$, and because $\lambda_1$ and $\dot{x}$ do not depend on $y$,

the analyses can be restricted to $[0, U'(C^*)(\theta - v)] \times [0, \infty]$ in the $(\lambda_1, x)$ phase space

where $\lambda_1$ is the shadow price of $x$ at a specific level of risk ($\delta$) and soil resources ($R$)

(fig. 3). Other important landmarks in phase space include:

$\lambda_1^*$, $x^*$ is the optimal or societal solution (i.e. it is a saddle point),

$x^*$ is the optimal level of biomass,

$\lambda_1^*$ is the optimal price with upper bound $\lambda_1 \leq U'(C^*)(\theta - v)$,

$x_c$ is the competitive solution,

$x_s$ is the level of $x$ where the regeneration rate $g^*(x_s)$ equals the discount rate $\delta$,

$x_u$ is the unexploited carrying capacity defined by $g(x_u) = 0$ and $x_u > 0$,

$x_z$ is a hypothetical extinction level.
Fig. 3. The \((\lambda_1, x)\) phase space with landmarks described in the text.

The competitive solution \(x_C\) arises when individuals of \(y\) pursue independent goals and each seeks to maximize their utility of consumption, disregarding all harvesting effects of depletion of the free access resource \(R\) via harvesting of \(x\). The competitive equilibrium solution \(x_C\) implies that the price \(\lambda_1=0\) (fig. 3), and ignores biological reality that there may be a critical level of \(x\) that leads to extinction of the resource (i.e. \(x_C \rightarrow x_E\)). Analysis shows that the lower the slope of \(\dot{x} = 0\) in the \((x, \lambda_1)\) state space, the larger is the distance between societal \((x^*)\) and competitive solution \(x_C\), and hence there is a larger chance that a competitive solution will lead to \(x_C \rightarrow x_E\) (Regev et al., 1998). This result is akin to the well known problem of over grazing.

**Comparing natural and industrial biomass systems**

In nature, the competitive solution \(x_C\) is irrelevant, as a stable ecosystem solution \(((\lambda_1^*, x^*), \bullet)\) evolves due to bottom-up factors \((R)\) and top-down controls that preclude
over exploitation of lower level trophic by higher ones (Hairston et al., 1960; Gutierrez & Regev, 2005).

The analogous situation in human economics is a societal solution wherein society establishes rules that keep over exploitation in check. This is the optimal societal solution ($x^*$, fig. 3) for resource exploitation by all farmers $y$ that maximizes the present value utility of individuals expending from the revenue stream in a manner that does not contribute to firm growth (consumption) and assures the persistence of the renewable resource ($x$) over an infinite time horizon (i.e., renewable resource sustainability). Note, this implies economic, social and ecological inputs with $x_s$ being the lower bound for the societal solution. So what might occur as the transition from harvesting grasslands to intensive agro-industrial management occurs? We examine qualitatively the effects on system landmarks by changing parameters $\theta$, $v$, $\delta$ and $R$ one at a time keeping the others constant (fig. 4). The isoclines for the initial system are indicated by solid lines (----), and those for parameter changes are indicated by dashed lines (- - - -).
Fig. 4. The \((\lambda_1, x)\) phase space of marginal and converted land with increases in (a.) efficiency \((\theta)\), (b.) costs \((v)\), (c.) decreasing soil fertility \((R)\) and (d.) increased risk \((\delta)\). Lines \((-\cdots-)\) are initial conditions of the ML and \((-\cdots-\cdots-)\) are due to resulting changes resulting from the conversion to biofuel productions.

**Efficiency parameter \((\theta)\)** – Increasing farmer efficiency \((\theta,\) i.e. gathering biomass and converting it to ethanol) increases the optimal marginal price \(\lambda_1^*\), decreases the optimal density \((x^*)\) and the competitive solution \((x_C)\), but does not affect \(x_d\) or the unexploited carrying capacity \(x_U\) (fig. 4a). The shift in the competitive solution is worrisome as it suggests that in an unregulated environment, over exploitation of the renewable resource will occur \((x_C \rightarrow x_E)\).

**Cost parameter \((v)\)** – If inputs costs \((v)\) increase, \(\lambda_1^*\) and \(x^*\) decrease and \(x_C\) increases, but as with increasing \(\theta\), \(x_d\) and \(x_U\) are not affected (fig. 4b), while the movement of \(x^*\), \(x_C\) and \(\lambda_1^*\) in opposite directions implies economic tradeoffs between increasing efficiency and increasing costs. In this analysis, costs are only those incurred by the farmer, and do not consider costs to the commons of increased release of CO\(_2\) that previously had been sequestered in the MLs (e.g. Fargione et al., 2008; Searchinger et al., 2008). If the environmental costs of increases in CO\(_2\) due to land conversion are included in \(v\), then \(\lambda_1^*\), \(x^*\) and \(x_C\) would be greatly reduced. Similarly, resistance in pests to GM toxins or resistance in weeds (Powles, 2008) to herbicides used in herbicide tolerant technologies would increase costs and have similar directional effects on \(\lambda_1^*, x^*\) and \(x_C\). The costs of pollution of the common by pesticides (e.g. ground water) and the subsequent health and non target effects (e.g. Relyea, 2006) are rarely assessed to the user. From a policy point of view, an increase in \(v\) as a pigouvian tax levied on harvesting capacity could be an effective policy for preserving the resource, but currently, a negative pigouvian tax is in force as biofuel producers are being given government subsides that under existing policies will in aggregate be over $92 billion within the 2006 - 2012 time frame (http://www.globalsubsidies.org) with refiners getting $1.01 per gallon and the growers $45 per ton of biomass (Robertson et al., 2008). The subsidy was designed to encourage
the development of biofuel technologies and but may result in over exploitation of limited soil resources and diminish biodiversity.

Risk ($\delta$) – If risk ($\delta$) increases, $\lambda^*$, $x^*$ and $x_\delta$ decrease but $x_C$ is unchanged (fig. 4c). Factors that increase risk, in addition to market risks, are climate change and decreasing availability of water, invasive species, and increasing impact of pests that are often exacerbated by pesticide use (Robertson et al., 2008). Among the direct market risks are changes in the demand for and lower prices of biofuels as new technologies come on line.

In addition, there is an interaction between increasing risk ($\delta$) and increasing efficiency ($\theta$) as both decrease the optimal density ($x^*$) with $\theta$ having a strong effects on lowering $x_C$. This suggests that when risk increases in the face of increasing efficiency, the tendency to over exploit increases, possibly to the point of extinction of the resource base.

Resource base ($R$) – Likely, industrial production of GMO biofuel plants cannot be sustained on MLs without inputs of fertilizer, and possibly water and pesticides ($\uparrow R$); inputs that will increase farmer costs (fig. 4d). Increasing $R$ shifts the $x$ null isocline rightward while the $\lambda_1$ isocline is unaffected as indicated by arrow $A$. Increasing $R$ causes a reduction in the marginal price $\lambda^*$ while increasing measures of system productivity, namely $x^*$, $x_U$ and $x_C$ (fig. 4c). Increases in $R$ will have a decreasing marginal effect on yield as $x^*$ approaches the new value of $x_U$.

If the land is abandoned and the inputs are removed, we posit that the land will be eroded below the initial value of $R$ for marginal lands shifting the $x$ null isocline leftward (arrow $B$) and possibly below $x_E$.

Discussion

The conversion of MLs for biomass/biofuel production solves the dilemma in the minds of some of the eco-social conflict between food and fuel production, but this may merely be an illusion as increasing market demands (and prices) may simply increase the
diversion of more agricultural as well as MLs for biofuel production that will further exacerbate world hunger (Ford Runge & Senauer, 2007). In an analysis, it is vital to note that the indirect impacts of biofuel production, and in particular the destruction of natural habitats (e.g. rainforests, savannah, or in some cases the exploitation of MLs which are in active use, even at reduced productivity by a range of communities, often poorer households and individuals) may have larger environmental impacts than the direct effects (Kammen et al., 2007). Chapin et al. (2000) claim the major causes of biodiversity loss on the planet are clearing and conversion of natural areas for monocultures and invasive of non-native species. Traits such as C4 photosynthesis, long canopy duration, lack of pests and diseases, and rapid spring growth, are also associated with invasiveness potential (Raghu et al., 2006) and should be of concern when introducing species for biomass production with these characteristics into new areas. These problems could be exacerbated on MLs, be they prairies or tropical forests, lands that while fragile provide important ecosystem services in terms of refuges for biodiversity, grazing, food, fibers and other benefits. MLs may require sizable inputs of nutrients and water to make production economically viable, and may carry the opportunity cost of forgone future carbon sequestration (Field et al., 2008). Industrialization of ML using agro-technical inputs to force higher yields will accelerate the diminishing of above and below ground biodiversity and in the long run will deplete soil fertility, function and structure through over harvesting, erosion and agro-technical inputs.

Currently, biofuel producers do not pay costs associated with the commons, and if they did, the push for biofuels would decrease. Instead government subsidies are providing negative pigouvian tax on harvesting capacity that encourages biofuel development. Furthermore, increased risk ($\delta$) decrease the marginal price of the biomass ($\lambda^*_i$) while increasing efficiency of production ($\theta$) increases the marginal price ($\lambda^*_i$) but decreases the competitive solution ($x_C$), and hence stimulates overexploitation of the system. The interaction of increasing risk and efficiency leads to lower $\lambda^*_i$ encourages over exploitation.
There are enormous differences in costs and benefits among biofuels, and the arguments that support one biofuel crop over another can easily change when one considers their full environmental effects (Scharlemann & Laurance, 2008). Zah et al. (2007) used two criteria to evaluate benefits: greenhouse-gas emissions relative to gasoline and overall environmental impact an aggregated measure of natural resource depletion and damage to human health and ecosystems. Zah et al. (2007) report that 21 out of 26 biofuels reduce greenhouse gas emissions by more than 30% relative to gasoline, but 12 out of 26 including U.S. corn ethanol, Brazilian sugarcane ethanol and soy diesel, and Malaysian palm-oil diesel have greater aggregate environmental costs than do fossil fuels (see Fargione et al., 2008). If the full environmental benefits of say tropical forest biodiversity conservation, hydrological functioning, and soil protection are included, the balance is further skewed (Laurance, 1999; Bala et al., 2007; Scharlemann & Laurance, 2008). Biofuels from residual products such as bio-waste or recycled cooking oil, and ethanol from grass or wood have the least environmental costs (see also Hill, Nelson, Tilman, Polasky, & Tiffany, 2006; Zah et al., 2007). While nonfood stocks offer energetic advantages, environmental, and economic criteria, but there can still be a positive carbon debt.

Switchgrass (Panicum virgatum) was chosen by the US Department of Energy’s Bioenergy Feedstock Development Program as a model energy crop due to its high biomass yields, broad geographic range, efficient nutrient utilization, low erosion potential, carbon sequestration capability, and reduced fossil fuel input requirements relative to annual crops (McLaughlin & Walsh, 1998; McLaughlin & Adams Kszos, 2005). Optimal types of biofuel crops are therefore likely to be perennial and perhaps indigenous plants currently well adapted for growth on ML, but GM improvements poses major ecological concerns of transgene flow to indigenous plants in geographic centers of diversity, and may potentially undermine biofuels’ sustainability (Stewart, 2007). Switchgrass and diverse mixtures of prairie grasses and forbs and woody plants can be grown on MLs with no or low fertilizer, pesticides, and energy inputs (Tilman et al., 2001, 2006) and if the process becomes competitive it can be converted into synfuel hydrocarbons or cellulosic ethanol with energy output/input ratios of energy of 4 (Hill et
al., 2006). However, the costs of pretreatment and enzymes will continue to make corn based ethanol with its established infrastructure competitive at least for the next decade (Robertson et al., 2008).

Tillman et al. (2006) found that harvesting a mixed prairie grass system for biofuel production could be sustainable with biomass yields increasing with increasing species diversity, and Fargione et al. (2008) conclude that the carbon debt of this system would be zero. Net energy gain from this cellulosic system would be comparable to the average yield for maize grain ethanol produced on fertile farmland. While this seems promising, the history of modern agriculture is one of intensification to increase yields, and the intensified cropping practices for ligno-cellulosic crops may include monocultures and high fertilizer and pesticide inputs (Parrish & Fike, 2005; Fike et al., 2006; Field et al., 2008).

Hence, despite carbon sequestering by switchgrass stands, their management for maximizing biomass production with high levels of nitrogen fertilization (Frank, Berdahl, Hanson, Liebig, & Johnson, 2004; Liebig, Johnson, Hanson, & Frank, 2005) release of N₂O and could significantly offset the greenhouse gas mitigation potential of such lands (Conant, Paustian, Del Grosso, & Parton, 2005; see Hill, 2007; Crutzen, Mosier, Smith, & Winiwarter, 2008). Furthermore, the gasoline offset would be small 2.5% (Milbrandt, 2005), and the spatial pattern of lignocellulosic crop production could have a large impact on wildlife habitat and biodiversity preservation (Cook, Beyea, & Keeler, 1991; Leemans, van Amstel, Battjes, Kreileman, & Toet, 1996; Green, Cornell, Scharlemann, & Balmford, 2005). The process of intensification could exacerbate the carbon debt on MLs.

Furthermore, will intensification of ML system for biofuel production push them to the point beyond their resilience capacity (sensu Holling, 1978), or can societal solutions be instituted to preserve the resilience and hence sustainability (sensu Gunderson, Holling, & Light, 1995; Walker et al., 2004)? The history of renewable resource management has not been good because human response and motivation are integral to the system being managed, and short-sightedness and greed make sustainable management difficult (Ludwig, Hilborn, & Walters, 1993). Our bio-economic model
suggests that the greed based competitive solution to resource management consistently
leads to the destruction of the resource base as a consequence (Regev et al., 1998). The
goal of maximizing biomass production on MLs (i.e. the competitive solution) for private
benefit may destroy ecosystem resilience that may “…not be detectable until it is severe
and … irreversible” (Ludwig et al., 1993). Will the conversion of MLs for biofuel
production simply be another evolving example of ecological mismanagement? This
scenario is not unreasonable and the European parliament is considering a moratorium on
biofuel due to concerns about economic sustainability and environmental impacts (Ruth,
2008).

One can envision a cycle of ML transformation and later abandonment in a state so
depleted of macro and micro-nutrients and altered soil properties that the land is unable to
regenerate to its original pre transformation biota. Holling proposed phases in renewable
resource utilization: exploitation, conservation, creative destruction and reorganization,
but in the case of MLs, the conservation phase may not occur leading directly to the
creative destruction phase wherein society must reorganize on badly degraded land that
may simply be left to recoup as best it can. This would be especially tragic in developing
countries currently targeted for biofuel production. The same reduced scenario applies to
other marginal fragile systems such as tropical rain forests converted to ranching or crop
production - the forest may not regenerate except on a much longer time scale.

Holling (2002) again provides intellectual leadership with his concept of adaptive
renewal cycle (panarchy) that explicitly takes into account fast/slow dynamics and cross
scale interactions and interdependencies (Gunderson & Holling, 2002; Folke, 2006). This
concept is important in our context because destruction of resilience (e.g. massive
decreases in soil structure and function, and biota) may occur rapidly, but the
reorganization phase may take considerably longer, especially if active community
involvement is lacking and “the costs of restoration is too high” (Farley & Daly, 2006).

The transformation of ML for biofuel production may yield a lasting legacy of
environmental disruption.

The transition of relatively undisturbed ML biota to an industrial biofuel monoculture
system is depicted fig. 5 as a shift from the evolved biota-nutrient-water state space of
native vegetation ($a$) to the state space of the biofuel cropping system ($b$) that can be maintained only with inputs of nutrients, water and pesticides. If the biofuel industry collapses for economic, social or biological reasons and the land is abandoned, the shift from state space $b$ to that of degraded land ($c$) may occur. The recovery of the land from state space $c$ to $a$ may be slow and at a rate ($\Delta$) that depends on the fragility and resilience capacity of the remaining components of the system. In the extreme, recovery of the biota may not occur because the system was pushed beyond its resilience capacity.

Herodotus’ in the 5th century B.C. summarized the problem of human management of lands succinctly: ‘‘Man stalks across the landscape, and desert follows his footsteps’’.

**Figure 5.** Phase space for the initial ecosystem (point $a$), the nutrient-water enriched system ($b$) and the abandoned degraded system ($c$).
REFERENCES


