A dynamic model of food and clean energy

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Abstract

In the midwestern United States, ethanol produced from corn is mixed with gasoline to meet clean air standards. Allocating land to produce clean fuel means taking away land from farming. We examine the use of a scarce fossil fuel that causes pollution but may be substituted by a clean fuel produced from land. When land is scarce, it is gradually shifted away from farming to energy production. However, when land is abundant, there may be a jump in the supply of clean energy. When the stock of pollution is regulated, the supply of clean energy may exhibit multiple discontinuities.

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1. Introduction

The Ford Motor Company has introduced several types of flexible fuel vehicles (FFVs) that run on E85, a mixture of 85\% ethanol (made from corn) and 15\% gasoline. There are 3.5 million FFVs already plying on US highways but only 400 fueling stations that supply E85. A bill passed by the US Senate provides tax credits...
for building E85 fueling stations. After the bill’s passage, United States Sen. Barrack Obama said: ‘a fuel made of 85 percent Midwestern corn is a lot more desirable than one made from 100 percent Middle Eastern Oil.’

The US Environmental Protection Agency is considering regulating a renewable energy standard, by which a designated fraction of all gasoline must come from renewable energy sources such as ethanol. These trends towards meeting clean energy goals through fuels produced from land imply an increased competition for scarce land resources, especially in agriculture. Policy makers in the US Midwest, for example are worried about the effects of rising ethanol consumption for energy on food prices (The New York Times, 2006). The European Union has proposed that by the year 2010, at least 5.75% of all transport fuels in the EU should be ethanol and other biological fuels. These policies have already led to a rapid increase in the production of biodiesel fuels in several EU countries.

In this paper, we develop a dynamic model that examines this trade-off between producing clean energy and using land for food production. The clean energy substitutes for a polluting non-renewable resource such as oil. We derive an equivalence between Ricardian land rent and the Hotelling rent for the nonrenewable resource (Ricardo, 1817; Hotelling, 1931). We show that the price of the clean fuel produced from land must lie within precise bounds dictated by the amount of available land and the demands for food and energy. These bounds determine the trigger price at which the land fuel is used for energy and the price at which the nonrenewable resource is completely exhausted. Supply of the land-based fuel may occur in a discontinuous fashion when land is relatively abundant. Ricardian rents to land as well as Hotelling rents to oil may increase over time.

We examine how environmental regulation imposed in the form of a limit on the stock of pollution may affect the substitution to a land-based fuel. Unlike abatement technologies which may be used only when regulation is binding, the land-based fuel may be deployed before the pollution stock is binding or later in time when pollution is no longer an issue.

There is a large literature on nonrenewable resources and pollution, including Forster (1980), Sinclair (1994), Ulph and Ulph (1994), Farzin (1996), Hoel and Kverndokk (1996), Tahvonen (1997) and Toman and Withagen (2000). The focus of these studies has largely been on the time path of pollution and carbon taxes. Hoel (1984) examines a model in which a nonrenewable resource has a perfect substitute in some of its uses but no substitute in others. He notes that resource prices may jump at the time when the substitute production comes into play. His focus is on market structure and price discrimination, not on the relationship between land and energy use. Chakravorty et al. (2006) extend a Hotelling model to explore the allocation of a polluting nonrenewable resource and a clean backstop. This paper is an extension of their approach, in which we explicitly model land allocation in an agricultural sector.

1‘High oil prices are dragging corn prices up with them, as the value of ethanol is pushed up by the value of the fuel it replaces,’ The New York Times (2006).

2Farzin and Tahvonen (1996) discuss a model with multiple pollution stocks but with different decay rates and a damage function for pollution.
that may produce both food and clean energy. The land endowment and magnitude of demands for food and energy affect substitution between the fossil fuel and the land fuel. On the other hand, pollution regulation in the energy sector affects the allocation of land in food production. In general, the main contribution of this paper relative to the above studies is in explicitly linking the use of a nonrenewable resource over time to the allocation of land.

Section 2 outlines the basic dynamic model with land. In Section 3, we develop intuition by examining polar cases of the model in which land is allocated for food alone, for both food and fuel after oil is completely depleted, and finally when both food and both sources of energy are produced. In Section 4, we integrate this land market equilibrium with the dynamic equilibrium in the oil market under environmental regulation. Section 5 discusses possible extensions of the basic model that incorporate stylized features of the energy and agricultural sector. Section 6 concludes the paper.

2. The model

We consider an economy in which utility $U$ at any given time $t$ is produced from food and energy, denoted, respectively, by $q_f$ and $q_e$. Utility is additive and is given by the sub-utility functions $U = u_f + u_e$. We further assume that $u_i : R_+ \rightarrow R, i \in \{f, e\}$ is of class $C^2$, strictly increasing and strictly concave, satisfying the Inada conditions $\lim_{q_i \rightarrow 0} u_i'(q_i) = +\infty$, where $u_i'(q_i) = d u_i/dq_i$. Denote by $p_i$ the marginal surplus function and by $d_i$ its inverse, i.e., $d_i(p_i) = p_i^{-1}(q_i) = u_i'(p_i)$.

There are two primary factors, land and a fossil fuel which we call oil. Land is assumed to be homogenous in quality, and its endowment is denoted by $\bar{L}$. Later we consider heterogeneous land quality. Land can be used to produce food or an energy crop such as corn that when converted to ethanol, serves as a clean substitute for oil. Let $L_i, i \in \{f, y\}$, be the portion of land dedicated to producing food and energy, respectively. Then the residual land $\bar{L} - L_f - L_y \geq 0$ is fallow. Without loss of generality, both the output of food and energy per unit of land can be normalized to one. Then the output per unit land for food and energy is $f(t) = L_f$ and $y(t) = L_y$. Let the average cost per unit of output be given by $c_i$, $i \in \{f, y\}$. These costs may include the cost of conversion of grain to ethanol. We assume that they do not vary with the volume of food or land fuel produced. Since food only comes from land, $q_f = f$ but energy may come both from land and oil, hence $q_e \geq y$.

Let $X(0)$ be the initial stock of oil, $X(t)$ the residual stock at time $t$ and $x(t)$ its rate of consumption so that $\dot{X}(t) = -x(t)$. Let $c_x$ be its average cost assumed to be constant and lower than the unit cost of the land fuel, $c_x < c_y$. The land fuel and fossil fuel are assumed to be perfect substitutes in final demand so that the total

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3In order to prevent notational clutter, we avoid writing the time argument explicitly wherever possible.
4The model may need to be significantly modified to consider energy sources such as wood from tree production because harvests tend to be discrete in time.
5Including the cost of extraction and processing.
6Even if the unit cost of land fuel were lower than that of oil, the land fuel may not be produced right away. In this sense, this framework is unlike the standard Hotelling model with a backstop.

consumption of energy at time $t$ is equal to the sum of their extraction rates:

$$q_e(t) = y(t) + x(t).$$

The land fuel is costly and produces no emissions. Let $\beta$ be the quantity of pollution (e.g., carbon) released into the atmosphere per unit of fossil fuel consumed and $Z(t)$ be this stock at time $t$, with $Z(0)$ the initial stock. As is standard in the literature we assume that there is some natural dilution of pollution that is proportional to the stock of pollution, $Z(t)$. Let $x > 0$ be the natural rate of decay. To keep the model simple, we abstract from considering costly pollution abatement policies, but discuss this issue later in the paper. The dynamics of pollution is given by

$$\dot{Z}(t) = \beta x(t) - \alpha Z(t).$$

We define pollution units such that each unit of oil produces one unit of pollution, i.e., $\beta$ is normalized to one. Thus we obtain

$$\dot{Z}(t) = x(t) - \alpha Z(t).$$

Let $\bar{Z}$ be the pollution stock quota exogenously imposed by an international agreement (such as the Kyoto Protocol), so that $\bar{Z} - Z(t) \geq 0$ at any time $t$. We define $\bar{x}$ as the maximum extraction rate of oil when this constraint is tight. From $Z(t) = 0$ and $\bar{Z}$, we get $\bar{x} = \alpha \bar{Z}$. The objective of the social planner is to maximize net aggregate surplus discounted at some constant rate $r > 0$. The planner allocates land for food and fuel production, and the scarce fossil fuel to solve the following problem:

$$\begin{align*}
\text{Max} & \int_0^{+\infty} \left( u_f(f) + u_e(x + y) - c_f L_f - c_y L_y - c_x x \right) e^{-rt} \, dt \\
\text{subject to} & \\
\bar{L} - L_f - L_y \geq 0, & L_y \geq 0, \\
\dot{X} = -x, & X(0) \text{ given, } X \geq 0, \ x \geq 0
\end{align*}$$

and

$$\dot{Z} = x - \alpha Z, \quad Z(0) \leq \bar{Z} \text{ given, } \bar{Z} - Z \geq 0.$$

The current value Lagrangian is

$$\ell = u_f(f) + u_e(x + y) - c_f L_f - c_y L_y - c_x x - \lambda x$$

$$+ \mu [x - \alpha Z] + \nu [\bar{Z} - Z] + \pi [\bar{L} - L_f - L_y] + \gamma_y L_y + \gamma_x x$$

and the first order conditions are

$$\frac{\partial \ell}{\partial L_f} = 0 \iff u'_f(f) = c_f + \pi.$$

---

\[
\frac{\partial \ell}{\partial L_y} = 0 \iff u'_y(x + y) = c_y + \pi - \gamma_y,
\]
(2)
\[
\frac{\partial \ell}{\partial x} = 0 \iff u'_x(x + y) = c_x + \lambda - \mu - \gamma_x
\]
(3)
together with the complementary slackness conditions:
\[
\gamma_x \geq 0, \quad \gamma_y x = 0,
\]
(4)
\[
\gamma_y \geq 0, \quad \gamma_y L_y = 0,
\]
(5)
\[
\pi \geq 0, \quad \pi [\bar{L} - L_f - L_y] = 0,
\]
(6)
where \(\gamma_x, \gamma_y\) and \(\pi\) are the relevant Lagrangian multipliers. Because of the Inada assumptions we have \(L_f > 0\), so we do not need a multiplier for nonnegativity of \(L_f\).

There will always be land under food production. The dynamics of the costate variables are determined by
\[
\dot{\lambda} = \rho \lambda - \frac{\partial \ell}{\partial x} \iff \dot{\lambda} = \rho \lambda \Rightarrow \lambda = \lambda_0 e^{\rho t},
\]
(7)
\[
\dot{\mu} = \rho \mu - \frac{\partial \ell}{\partial Z} \iff \dot{\mu} = (\rho + \alpha)\mu + \nu,
\]
(8)
and
\[
v \geq 0 \quad \text{and} \quad v[\bar{Z} - Z] = 0,
\]
(9)
where \(\lambda_0 = \lambda(0)\). The costate variable \(\mu\) is nonpositive. If \(Z < \bar{Z}\) over some time interval \([t_0, t_1]\), then \(v = 0\) and \(\mu(t) = \mu(t_0) e^{(\rho + \alpha)(t - t_0)}\), \(t \in [t_0, t_1]\). Lastly, the transversality conditions at infinity are
\[
\lim_{t \uparrow +\infty} e^{-\rho t} \lambda(t) X(t) = \lambda_0 \lim_{t \uparrow +\infty} X(t) = 0,
\]
(10)
\[
\lim_{t \uparrow +\infty} e^{-\rho t} \mu(t) Z(t) = 0.
\]
(11)
We will use the term ‘full marginal cost’ to mean the monetary cost of a good augmented by the relevant shadow price. The full marginal costs are \(c_f + \pi\) for food, \(c_y + \pi\) for the land fuel, and \(c_x + \lambda - \mu\) for oil. Note that the marginal costs for food and fuel must include a land rent component.

3. Land allocation between competing uses

In this section we determine optimal land use and the supply of food and energy. To develop intuition, we examine two polar cases in which land is used only for food production and when it is used both for food and energy when oil is completely exhausted. These are not meant to be realistic scenarios but help understand the nature of the solution in the general case when land is used both for food and energy in the presence of polluting fossil fuel resources.

3.1. Land is used only for food

Define $L_f^f \leq \bar{L}$ as the land parcel under food production if no energy is being produced from land. We use the superscript $f$ to denote equilibrium values in this food only model. Then the remaining land $\bar{L} - L_f^f \geq 0$ will be fallow. Let $\pi_f$ be the corresponding rent to land. Then $\pi_f(L_f^f) = u'_f(L_f^f) - c_f$. If $\pi_f(\bar{L}) > 0$, all the land must be in use, so that $L_f^f = \bar{L}$. When land is abundant or demand for food is low, $L_f^f$ solves $u'_f(L_f^f) - c_f = 0$ and equilibrium land rent $\pi_f$ is zero. We will ignore the degenerate case in which rents go to zero exactly when all available land is used. We assume that if $\pi_f = 0$, then $L_f^f < \bar{L}$, some land is always left fallow.

Define $p_f^y$ as the full marginal cost of the land fuel when land rents equal $\pi_f$, i.e., $p_f^y \equiv c_y + \pi_f$. Then $p_f^y \geq c_y$. If the price of energy is less than $p_f^y$, land is more productive in food production. Hence no clean fuel will be produced and only oil must be used for energy. The price $p_f^y$ thus serves as a lower bound for the price of energy at which land fuel production becomes competitive. If $\pi_f$ is zero, then $p_f^y = c_y$. The trigger price for the land fuel is its average cost. The choice of $L_f^f$ is shown in Fig. 1. The function $\pi_f^1$ denotes the situation in which some land is left fallow, and $\pi_f^2$ when all land is used in food production.

3.2. The steady state: land use when oil is exhausted

When oil is exhausted, we achieve a steady state in which only the land fuel must supply energy. Let $L_f^y$ and $L_y^y$ be land parcels allocated for the production of food and fuel, and $\pi^y$ the corresponding equilibrium land rent, where the superscript ‘$y$’ denotes equilibrium values for this model. With no oil, pollution is a nonissue since emissions are zero. The maximization problem (P) reduces to

$$\max_{(L_f^y, L_y^y)} \int_0^{+\infty} \{u_f(f) + u_e(y) - c_f L_f - c_y L_y \} e^{-\rho t} \, dt$$

(P1)

Fig. 1. Land is used only for food.
subject to
\[ \bar{L} - L_f - L_y \geq 0. \]

Because of the Inada conditions, we must have \( L_y > 0 \). The necessary and the complementary slackness conditions are

\[ u'_f(f) = c_f + \pi, \]
\[ u'_e(y) = c_y + \pi, \]

and

\[ \pi \geq 0 \quad \text{and} \quad \pi[L - L_f - L_y] = 0. \]

With no stock dynamics, (P1) is a static problem. Let \( \pi_y(L_y) \) be the rent to land allocated for land fuel production, i.e., \( \pi_y(L_y) = u'_f(L_y) - c_y \). All the available land will be used for food and energy production if equilibrium land rents \( \pi^f \) are equal and strictly positive, i.e., \( \pi_f(L_f) = \pi_y(\bar{L} - L_f) > 0 \), as shown in Fig. 2. When land is abundant or demands are small, each marginal product may be zero, i.e., \( L^y_y \) solves \( \pi_f(L_f) = 0 \). In this case land allocated for food is equal to that in the previous model with no energy production, and \( L^y_y \) solves \( \pi_y(L_y) = 0 \), with \( L^y_f + L^y_y < \bar{L} \) and the common land rent \( \pi^f = 0 \). Some land is left fallow. If equilibrium land rents are zero in the model with the land fuel, it cannot be strictly positive in the food only case when there is no competition for land. That is, we cannot have \( \pi^f = 0 \) and \( \pi^f > 0 \).

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Fig. 2. Land is used both for food and clean energy.
3.3. Land use for food and energy when oil is available

We now consider land allocation when oil is still available. Define $p^y_f$ as the full marginal cost of the clean fuel when the land rent is equal to $\pi^y$, i.e., $p^y_f = c_y + \pi^y$. Rents must be higher in the presence of competing uses, hence $\pi^y > \pi^f$. This implies that $p^y_f > p^f_y > c_y$. We then have $p^y_f > c_y$ if $\pi^f > 0$ and $p^y_f > p^f_y$ if $\pi^y > \pi^f$. We will see below that the price of energy is at most equal to $p^y_f$, the highest price reached once oil is exhausted. If rents are zero both in the food only case and in the steady state, $\pi^y = \pi^f = 0$, then some land must be fallow, i.e., $L^y_f + L^f_f < \bar{L}$.\(^8\) In the food only model, there is no competition for land, hence rents will achieve some lower bound, while in the steady state, all energy must come from the land fuel, so that rents achieve some upper bound.

Consider energy supply for given energy prices $p_e \leq p^y_f$. Define $\pi(p_e)$ as the land rent for which the full marginal cost of the land fuel is equal to the price of energy $p_e$. If this energy price $p_e$ is less than $c_y$, $\pi(p_e)$ is zero. Otherwise, $\pi(p_e) = p_e - c_y$ when $c_y < p_e \leq p^y_f$. Now consider the polar case when all available land is used under food production. That is, $\pi^f > 0$. This may happen when the demand for food is high or the endowment of land is low. Then $c_y < p^y_f \leq p^f_y$. For energy prices $p_e < p^f_y$, we have $\pi(p_e) < \pi^f$. The rent under food production is higher than in fuel production, hence all the available land must be used to grow food and there will be no land fuel supplied to augment the use of oil. For higher energy prices $p_e \in [p^f_y, p^y_f]$, we have $\pi(p_e) > \pi^f$. Now the land fuel is competitive in the allocation of land, hence $\gamma > 0$ and $\gamma_y = 0$. Equalization of land rents implies $u'_f(L_f) - c_y = p_e - c_y$ so that $dL_f/dp_e = 1/u'_f(L_f) < 0$.

A higher price of energy induces a decrease in the land allocated to food and an increase in the land allocated to fuel. Let $L_f(p_e)$ solve the above necessary condition for $p_e \in (p^f_y, p^y_f]$ and equal zero for $p_e \leq p^f_y$. Then the supply of land fuel as a function of the price of energy $p_e$ given by $y(p_e)$, is $y(p_e) = \bar{L} - L_f(p_e)$.

Let the portion of energy supplied by oil be denoted by $d_e(p_e)$. It must equal the aggregate demand for energy net the quantity supplied by the land fuel, $d_e(p_e) - y(p_e)$. Because $\pi^f > 0$, when $p_e = p^f_y$, we have $d_e(p^f_y) = d_e(p^y_f)$ and $y(p^f_y) = 0$. No land fuel is being supplied at this price. When $p_e = p^y_f$, $d_e(p^y_f) = y(p^y_f)$. At the steady state, all energy comes from the land fuel. Since $d_e(p_e)$ is decreasing while $y(p_e)$ is increasing we conclude that $d_e(p_e)$ must be decreasing from $d_e(p^f_y)$ to zero at $p_e = p^y_f$. Furthermore $d_e(p_e)$ is continuous at $p_e = p^f_y$ although nondifferentiable as illustrated in Fig. 3.

Now consider the opposite case when land is abundant both for food and energy or their demands are small, i.e., $\pi^f = \pi^y = 0$. Then $p^f_y = p^y_y = c_y$. Since marginal land rent is zero, for any price of energy $p_e$ that is higher than the trigger price $c_y$, all energy must be supplied by land. The demand for oil decreases discontinuously from $d_e(c_y)$ to a value that is indeterminate within the interval $[0, d_e(c_y)]$ and is then exhausted. This is the case in which the land fuel acts as a pure backstop at the price $c_y$, as shown in Fig. 4.

\(^8\)We ignore the degenerate case when $\pi^y = \pi^f = 0$ and $L^y_f + L^f_f = \bar{L}$. 

Finally, consider the most plausible case when land is fallow under food production but not in the steady state, i.e., \( \pi^f = 0 < \pi^y \). This case may arise if there is enough land for food production but not for producing both food and energy, or if the demand for food is low relative to the demand for energy. The marginal land rent under food production is zero, but is strictly positive when both food and energy are being produced after the exhaustion of oil, \( p^f_y = c_y \) and \( p^e_y > p^f_y = c_y > c_x \). This case is best understood by checking Fig. 2 in which the trigger price for land fuel at the equilibrium land rent (not shown) is the unit cost \( c_y \). At prices \( p^e > p^f_y = c_y \) a strictly positive quantity of land fuel is supplied because \( \pi^y(p_y) > \pi^f \). The marginal rent
increases until it reaches the value $\pi^u$ when all oil is exhausted. The value of $L_f$ is strictly positive and bounded from above by $L_f < \bar{L}$, so that $\lim_{p_e \downarrow c_y} (\bar{L} - L_f(p_e)) > 0$ implies $\lim_{p_e \downarrow c_y} y(p_e) < d_x(p_y)$ when $p_y < p_f$, $y(p_e) = 0$. Thus at $p_e = c_y$, $y(p_e)$ jumps from zero to $\lim_{p_e \downarrow c_y} (\bar{L} - L_f(p_e)) = \bar{L} - L_f > 0$. The case is illustrated in Fig. 5. Because some land is fallow at the trigger price, there is a discrete jump in the initial supply of land fuel as shown. Subsequently, the increase in energy prices leads to a continuous increase in the supply of the land fuel.

We can summarize the key results as follows:

**Proposition 1.** When land is scarce or the demand for food is high, the supply of the land fuel occurs gradually as energy prices rise. However, when land is abundant or there is a low demand for food, there is a discontinuous increase in land fuel supply at the trigger price.

### 4. Dynamics of land fuel supply

In this section we impose dynamics on the above Ricardian framework. First, we consider the Hotelling model without any environmental regulation. This is problem (P) without the constraint $\dot{Z} - Z \geq 0$. The modified condition (3) now becomes $u'(x + y) = c_x + \lambda - \gamma_x$ and conditions (8), (9) and (11) no longer hold.

Since $c_x < c_y \leq p_f^x \leq p_y$, the interval $[c_x, p_y]$ is nondegenerate. For any $\lambda_0 \in (0, p_y - c_x)$ let $p_x(\lambda_0)$ be the Hotelling price of oil given by $p_x(\lambda_0) = c_x + \lambda_0 \omega_x$. Let $G^y(\lambda_0)$ be the time at which this price is equal to the steady state price $p_y$, i.e., all oil is exhausted at time $G^y(\lambda_0) = \rho^{-1} \left[ \ln(p_y^y - c_x) - \ln \lambda_0 \right]$. Let $X(\lambda_0)$ be the cumulative

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consumption of oil over the time interval \([0, \Gamma^y(\lambda_0)]\) along this Hotelling price path. The aggregate supply of oil is \(X(\lambda_0) = \int_0^{\Gamma^y(\lambda_0)} d_x(p_x(\lambda_0)) \, dt\). Let \(x(\lambda_0)\) and \(y(\lambda_0)\) denote the oil and land fuel consumption paths corresponding to the Hotelling price path \(p_x(\lambda_0)\). Define \(\Gamma^f(\lambda_0)\) as the time at which \(p_x(\lambda_0) = p^f_x\), that is \(\Gamma^f(\lambda_0) = \rho^{-1}\ln(p^f_x - c_x) - \ln \lambda_0\). This is the time at which the price of oil hits the trigger price when land fuel supply begins. Then for \(\pi^v > 0\), that includes the two cases \(\pi^v > \pi^f > 0\) and \(\pi^v > \pi^f = 0\), we have

\[
x(\lambda_0) = \begin{cases} 
  d_x(p_x(\lambda_0)) = d_x(p^f_x(\lambda_0)), & 0 \leq t < \Gamma^f(\lambda_0), \\
  d_x(p_x(\lambda_0)) < d_x(p^f_x(\lambda_0)), & \Gamma^f(\lambda_0) < t < \Gamma^y(\lambda_0), \\
  0, & \Gamma^y(\lambda_0) \leq t,
\end{cases}
\]

\[
y(\lambda_0) = \begin{cases} 
  d_x(p_x(\lambda_0)) - d_x(p^f_x(\lambda_0)), & 0 \leq t < \Gamma^f(\lambda_0), \\
  \pi^v, & \Gamma^y(\lambda_0) \leq t,
\end{cases}
\]

where \(\pi^v = L_y^v\). For \(\lambda_0 \in (p^f_x - c_x, p^v_x - c_x)\), the phase during which oil supplies all of the energy demand disappears because the unit cost of the land fuel is lower than the full marginal cost of oil, i.e., \(\lambda_0 + c_x < p^f_x\). When \(\pi^f > 0\), as shown in Fig. 3, oil supplies all the energy until the Hotelling price equals the trigger price \(p^f_x\). Above this price, the supply of oil is augmented by fuel from land. The supply of the land fuel increases until oil is completely exhausted at price \(p^v_x\). When \(\pi^f = 0\) but \(\pi^v > 0\), the supply of the land fuel is shown in Fig. 5. Oil supply is positive in the entire price range \((p^f_x, p^v_x)\). Oil is exhausted when the price reaches \(p^v_x\). Finally, when \(\pi^v = 0\), then \(p^v_y = p^v_x = c_y\), the land fuel acts as a pure backstop resource. Only oil is supplied until time \(\Gamma^f = \Gamma^y\), shown in Fig. 6. The intermediate phase of simultaneous extraction that occurred previously now disappears.

4.1. Supply of the land fuel under environmental regulation

Now we consider a cap on the stock of emissions.\(^9\) This constraint may reduce the use of oil or substitute it with energy from land. The land fuel is more costly than oil, and supplying it reduces the consumption of food when land is scarce. For this

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\(^9\)A cap on the stock of pollution is a special case of a more general damage function assumed in several related studies, such as Farzin and Tahvonen (1996). In our model we implicitly assume zero damages below the ceiling and infinite damages beyond it. This specification may be thought of as a piecewise approximation of a general convex damage function in which marginal damages are positive even at lower levels of the pollution stock. In the next section we discuss how a damage function may be introduced in the present framework.
exercise to be meaningful, we assume that the ceiling constraint is binding when imposed on the standard Hotelling case with no regulation.\(^\text{10}\)

If \(\bar{t}\) is the final instant of time at which the constraint is tight, then \(m(t) = 0\) beyond \(\bar{t}\) since the environmental constraint no longer binds and resources are allocated as in a Hotelling model. Let \(\tau\) be the first time instant at which the ceiling constraint is binding \((\bar{Z}_0 < \bar{Z} \implies \tau > 0)\). Over the time interval \([0, \tau]\) the constraint is not binding but will do so later in time. Since \(\bar{Z} - \bar{Z} > 0\) then \(\nu = 0\) so that \(\mu = \frac{\mu_0 e^{(\rho + \alpha)t}}{\alpha}\) with \(\mu_0 < 0\) and the full cost of the fossil fuel is denoted by \(p_c\) such that \(p_c(\hat{\lambda}_0, \mu_0) = c_x + \hat{\lambda}_0 e^{\rho t} - \mu_0 e^{(\rho + \alpha)t}\).\(^\text{11}\) Let \(Z(\lambda_0, \mu_0)\) be the path of the stock of pollution corresponding to the price path \(p_c(\hat{\lambda}_0, \mu_0)\), i.e., the path defined by \(dZ/dt = dx (p_c(\hat{\lambda}_0, \mu_0)) = zZ\), given an initial \(Z(0)\).\(^\text{12}\)

Whether the land fuel is economically feasible depends upon whether the constrained oil extraction at the ceiling \(\hat{x}(= \bar{Z})\) is higher or lower than demand at the trigger price given by \(d_c(p_y^f)\). If \(\hat{x} > d_c(p_y^f)\), then the constraint is not tight enough or the opportunity cost of the land fuel is relatively high so that using land to provide supplementary clean energy to satisfy the regulatory constraint is cost prohibitive. That is, the price at which the consumption of oil is constrained is lower than the trigger price at which the land fuel is competitive, \(p_y^f\). We now reexamine the three cases discussed earlier from the point of view of environmental regulation.

\(^\text{10}\)If the ceiling were set too high or the stock of oil was low, then a ceiling may not be binding over any nonzero interval of time and the pure Hotelling result will hold.

\(^\text{11}\)Note that the shadow price of the externality \(m(t)\) is nonzero from the beginning of the planning horizon. Before the ceiling is achieved, \(m(t)\) rises at an exponential rate given by \(\mu = \frac{\mu_0 e^{(\rho + \alpha)t}}{\alpha}\). During the period when the ceiling is binding, the path of \(m(t)\) is given by (8) and the multiplier \(\nu\) is in general nonzero.

\(^\text{12}\)We use the same notation as in the previous section, although the variables here (e.g., \(p_c\)) refer to a different model, the one with regulation. Since the context is clear, hopefully this notational simplicity will not be confusing.

4.2. Land is used only for food initially

Suppose all land is used for food at the beginning, i.e., $\pi^f > 0$. Here $p_f^y > p_f^l > c_y > c_x$ and the demand for oil $d_x$ is continuous at the trigger price $p_f^y$. The price $\bar{p}_c$ at which $d_x(p_x) = \bar{x}$ is well defined. If $\bar{p}_c > p_f^l$, as shown in Fig. 7, the land fuel is competitive at prices $p_e \in (p_f^y, \bar{p}_c)$. It is used along with oil before regulation becomes binding. As shown in the figure, there is an initial phase during which the stock is lower than the ceiling and the price of fuel is given by $p_e(\lambda_0, \mu_0)$. This phase may include a segment during which both fuels are used simultaneously. At time $t = 0$, $p_e(\lambda_0, \mu_0) < p_f^y$. If $p_e(\lambda_0, \mu_0) > p_f^y$ then both fuels must be used from the beginning. During this initial
phase the pollution stock is increasing. The ceiling is attained at time $t$ at which $Z(l_0, \mu_0) = \bar{Z}$ and $p_e(l_0, \mu_0) = \bar{p}_e$.

At the ceiling, the price of fuel is constant at $\bar{p}_e$. Oil consumption is constrained at $\bar{x}$ and land fuel consumption is given by $y = d_e(\bar{p}_e) - d_x(\bar{p}_e) > 0$. During this time the shadow price of pollution $\mu$ is increasing, i.e., decreasing in absolute value. At the end of this phase at $t = \bar{t}$, pollution is no longer an issue and $\mu = 0$ for the rest of the planning horizon. The next phase is a pure Hotelling phase during which $p_e = p_x(l_0)$. Oil consumption is decreasing but land fuel supply is increasing in response to the rise in prices. At time $t = \Gamma^y(l_0)$, oil is exhausted. Beyond this time, the land fuel is the only source of energy.\footnote{For technical details of this solution, please see Appendix A available to the reader through the Supplement Archive of this journal.}

In this scenario, the production of land fuel begins at $t = \Gamma^l(l_0)$, before the ceiling is attained. Land allocated to food production declines until the pollution stock hits the ceiling at $t = \bar{t}$. At the ceiling, the supply of the clean fuel is constant, hence food production and prices are also constant. Once the ceiling is no longer constrained from $\bar{t}$ onwards, food production continues to decline until it reaches the steady state at $t = \Gamma^y(l_0)$. Thus land allocated to food production is constant in an initial period, declines before the ceiling takes effect, then is constant for another period and finally declines. Environmental regulation leads to constant food output and prices over a period of time. If there was no regulation, the decline in food production would be gradual until oil was exhausted and land fuel supply was at its maximum level. If the price at the ceiling is lower than the minimum price at which the land fuel becomes economical, i.e., $\bar{p}_e < p^f_y$, only oil is consumed at the ceiling and the land fuel is supplied after the ceiling period is completed.\footnote{For reasons of space, this case is not illustrated in the paper.}

4.3. Land is fallow under food production but not in the steady state

In this case, land rents are zero under food production but strictly positive in the steady state when both food and energy are produced, i.e., $\pi^f = 0$, $\pi^y > 0$. The solution depends on the relative magnitude of demand for oil at the trigger price for the land fuel and the level of oil use at the ceiling. If $\bar{x} < \lim_{p_e \downarrow p^f_y} d_x(p_e)$, then the price of energy at the ceiling is higher than the trigger price, $\bar{p}_e > p^f_y$. Only the land fuel is used at the ceiling. But if $\bar{x} > d_e(p^f_y)$, then oil is used exclusively at the ceiling, and the clean fuel is used only in the post-ceiling period.

However, if $\lim_{p_e \downarrow p^f_y} d_e(p_e) < \bar{x} < d_e(p^f_y)$, there is a jump discontinuity when the energy price equals $p^f_y$. As shown in Fig. 8, at the end of the first phase oil consumption is discontinuous and falls from $d_x(p^f_y)$ to $\bar{x}$. The deficit is supplied by land fuel. The reason for the discontinuity is that there is fallow land available, and only a portion of it is cultivated for energy at the instant the ceiling becomes binding. Demand for energy can be more than satisfied by available land. Energy demand at
the ceiling is strictly greater than demand for oil at the trigger price $p_f^y$, but strictly less than unregulated aggregate energy demand at that price. There is no impact on food production because the amount of land that is fallow exceeds the land fuel needed at the ceiling, given by

$$d_e(p_e) \frac{C_0}{\lim_{p_e \downarrow p_f^y} d_e(p_e)}.$$ 

Thus some land continues to be fallow until again at time $\bar{t}$ when oil consumption falls again from $\bar{x}$ to $\lim_{p_e \downarrow p_f^y} d_e(p_e)$ and clean fuel consumption jumps up by the same amount. Now all land is used up. Food consumption gradually decreases from $f^f$ to a steady level of $f^v$.

The optimal values of $\lambda_0, \mu_0, \bar{\tau}, \tilde{\tau}$ and $\Gamma^v$ solve the following five equations system: the cumulative demand/supply balance for oil,

$$\int_0^{\tau} d_e(c_x + \lambda_0 \omega^\mu - \mu_0 e^{(\rho + \alpha) t}) dt + \int_{\bar{\tau}}^{\tilde{\tau}} d_e(c_x + \lambda_0 \omega^\mu) dt = X^0;$$

the pollution stock continuity equation at $\bar{\tau}$, $Z(\lambda_0, \mu_0) = \bar{Z}$; the price continuity equations at $\bar{\tau}$ and $\Gamma^v$:

$$p_e(\lambda_0, \mu_0) = \beta_e,$$

$$p_e(\lambda_0) = p_e^f$$

at $t = \bar{\tau}$, $p_e(\lambda_0) = p_e^f$ at $t = \tau$, and $p_e(\lambda_0) = p_e^f$ at $t = \Gamma^v(\lambda_0)$. 

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15The optimal values of $\lambda_0, \mu_0, \bar{\tau}, \tilde{\tau}$ and $\Gamma^v$ solve the following five equations system: the cumulative demand/supply balance for oil, 

$$\int_0^{\tau} d_e(c_x + \lambda_0 \omega^\mu - \mu_0 e^{(\rho + \alpha) t}) dt + \int_{\bar{\tau}}^{\tilde{\tau}} d_e(c_x + \lambda_0 \omega^\mu) dt = X^0;$$

the pollution stock continuity equation at $\bar{\tau}$, $Z(\lambda_0, \mu_0) = \bar{Z}$; the price continuity equations at $\bar{\tau}$ and $\Gamma^v$:

$$p_e(\lambda_0, \mu_0) = \beta_e,$$

$$p_e(\lambda_0) = p_e^f$$

at $t = \bar{\tau}$, $p_e(\lambda_0) = p_e^f$ at $t = \tau$, and $p_e(\lambda_0) = p_e^f$ at $t = \Gamma^v(\lambda_0)$. 

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4.4. Land is abundant both for food and energy

In this case marginal rents are zero, \( p' = p_y = 0 \). See Fig. 9 for the case \( \bar{x} < d_e(p_y) \). Demand for oil at the ceiling is lower than demand for energy at the trigger price. Supply of the land fuel starts exactly at the ceiling and there is no Hotelling phase after the ceiling. Oil supply exhibits a discontinuity from \( d_e(p_y) \) to \( \bar{x} \). The difference is supplied by the clean fuel but all available land is still not utilized. Oil is exhausted exactly at time \( \bar{t} \) when the land fuel supply jumps up from \( d_e(p_y) - \bar{x} \) to \( d_e(p_y) = y_f \) at the steady state.

Alternatively, the clean fuel may work as a textbook backstop resource and may not supplement the fossil fuel, when \( \bar{x} > d_e(p_e) = d_e(c_y) \). Demand for oil is less than demand for energy at the ceiling. Only oil is used at the ceiling and for a time period when the ceiling is no longer binding. It is finally exhausted at the cost of the

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**Fig. 9.** Oil is exhausted exactly when regulation ceases to bind.
backstop, $c_y$ and is completely replaced by the land fuel. The land fuel is available at unit cost since land rents equal zero.

We summarize the main results as follows:

**Proposition 2.** With environmental regulation, the supply of the land fuel may occur before regulation becomes binding. When land is abundant, land fuel supply may exhibit multiple discontinuities, first at the trigger price and then again when regulation ceases to bind. Imposing a ceiling on the stock of emissions may lead to a constant production of food over a period of time.

5. Extensions of the basic model

In this section we consider several possible extensions of the above framework based on typical features of the agricultural and energy sector. For each case we discuss how the above solution will change as well as the resulting implications for the introduction of land-based fuels. It is important to note that without explicitly solving each of the models below, it is hard to tell which of our results will continue to hold. Thus the purpose of this section is to provide a flavor of some of the issues involved in bridging the gap between the simple model described above and the complex real-world issues that must be considered in order to answer important policy questions.\(^{16}\)

5.1. Costly pollution abatement

Costly pollution control policies such as through more efficient appliances (e.g., scrubbers) or sequestration could be used to reduce the stock of emissions.\(^{17}\) Suppose the cost of reducing one unit of pollution is given by the constant $c_a$, where $a$ denotes units abated. Then the total instantaneous abatement cost is equal to $c_a a$ and the new dynamics of the pollution stock is given by $\dot{Z} = x - a - a \dot{Z}$. The new maximum extraction rate of oil at the ceiling will be $\bar{x}(a)$ where $\bar{x}(a) = a + a \dot{Z}$. When $a = 0$, we get back the original extraction rate $\bar{x}$. The optimization program (P) must now be modified by including abatement $a$ as a choice variable. This new program (P2) yields the following additional conditions:

$$\frac{\partial \ell}{\partial a} = 0 \iff -\mu = c_a - \gamma_a,$$

(12)

$$\gamma_a \geq 0 \text{ and } \gamma_a a = 0,$$

(13)

where $\gamma_a$ is a Lagrangian multiplier. Define $p_e(\lambda_0)$ as the full marginal cost of the clean fossil fuel including the marginal cost of abatement but excluding the shadow...

\(^{16}\)Each of these issues could be considered in future research both for further qualitative characterization and the development of models for policy analysis.

\(^{17}\)Technical details characterizing the optimality of the abatement policy are contained in Appendix B which is available to the reader from the Supplement Archive of this journal.
cost of the ceiling constraint: \( p_e(\lambda_0) = c_x + \lambda_0 e^{rl} + c_a \). Abatement will not occur if the full marginal cost with abatement is higher than the one with no abatement. There is no benefit from abating when the stock of pollution is strictly below the ceiling. Abatement is costly and reducing pollution when the constraint is not binding confers no benefit. Abatement must thus occur only at the ceiling.

Abatement must also occur only at the beginning of the ceiling period, if at all. The marginal cost of oil under abatement is upward sloping, since it depends upon the price of oil which rises over time. If abatement were optimal, then this graph must cut the horizontal ceiling price \( \bar{p}_e \) at some time period, say \( \bar{t} \). Before this time, the abatement marginal cost is below \( \bar{p}_e \) hence abatement is economical, and after \( \bar{t} \), the marginal cost is above \( \bar{p}_e \), hence abatement becomes too expensive. Given that the unit cost of pollution control is constant and the ceiling is tight, the earlier it is done during the ceiling period the better, since that allows increased use of cheap oil earlier in time.

Both use of the land fuel and abatement are substitutes for the fossil fuel, but operate differently. Abatement may happen only at the ceiling and must commence at the beginning. The use of the land fuel may start before the ceiling, and once energy production from land begins, it will always be part of the fuel mix. This is because the scarcity of oil drives the price of oil higher, inducing increased substitution of land away from food production. The land fuel may be supplied starting from before the ceiling is binding, interior to the ceiling or after the ceiling no longer holds.

5.2. Increasing marginal cost of fossil fuel extraction

Suppose the marginal cost increases with a reduction in the available stock of the fossil fuel, as is often assumed in the Hotelling literature. It can be written as \( c_x(X) \) with \( c'_x(X) < 0 \) and \( c''_x(X) > 0 \). Marginal cost is increasing as the stock declines and convex. In this case, condition (7) becomes

\[
\dot{\lambda} = \rho \lambda - \frac{\partial \ell}{\partial X} \quad \Rightarrow \quad \dot{\lambda} = \rho \lambda + c'_x(X).
\]

The shadow price of the nonrenewable resource \( \lambda(x) \) no longer rises at an exponential rate. It is not obvious how the price of the nonrenewable resource will behave relative to the model with constant extraction costs. But if the initial cost and the aggregate stock remains the same but the cost of the nonrenewable rises significantly with depletion, the transition to the land-based fuel will be quicker. It is likely that the nonrenewable resource will be used for a longer time horizon in which case more of the land fuel will be used earlier in time and hence, less food will be produced, ceteris paribus.

5.3. Heterogeneity in land quality

We assume homogenous land quality although land quality exhibits large variation from one location to another. There are several different ways in which
and the nonnegativity conditions given by energy production, respectively. Then aggregate food and clean energy production is

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function with the new constraint of production for both food and energy. Denote the quality of land as

simplest way to think of the problem is that a higher land quality implies a lower cost
developing countries may be lower than that for developed countries. Perhaps the
of cultivating land may vary by location. For example, the cost
quality with comparative advantage in producing food or energy crops. Or, the cost
one can model differences in land quality. For example, lands may be of varying
quality with comparative advantage in producing food or energy crops. Or, the cost
cultivating land. However, intramarginal rent for qualities
lowest quality land exploited at any instant. Then some land is fallow and rent is zero
solving this model explicitly, we can obtain several insights. Suppose


where the highest quality is normalized to $\theta = 0$ and the lowest quality is denoted by $\theta$. Then the cost of producing food or energy from land is given by the unit cost

developmental land area of quality $\theta$ devoted to food and energy production, respectively. Then aggregate food and clean energy production is
given by $f = \int_0^\theta l_f(\theta) \, d\theta$ and $y = \int_0^\theta l_y(\theta) \, d\theta$. The optimization problem (P) becomes

$$
\max_{(l_f(\theta)l_y(\theta),x)} \int_0^{+\infty} \left\{ u_f(f) + u_e(x + y) - \int_0^\theta [c_f(\theta)l_f(\theta) + c_y(\theta)l_y(\theta)] \, d\theta - c_x x \right\} e^{-rt} \, dt
$$

with the new constraint

$$
l_f(\theta) + l_y(\theta) \leq g(\theta), \quad \theta \in [0, \theta]\n$$

and the nonnegativity conditions $l_f(\theta) \geq 0$ and $l_y(\theta) \geq 0$. The costs of cultivation are now aggregated over each land quality and the planner cannot allocate more land
than available for type $\theta$ given by $g(\theta)$. The above reformulation of the basic model yields the following necessary conditions:

$$
\frac{\partial \ell}{\partial l_f} = 0 \Leftrightarrow u_f' \left( \int_0^\theta l_f(\theta) \, d\theta \right) = c_f(\theta) + \pi(\theta) - \gamma_f(\theta),
$$

$$
(1a)
$$

$$
\frac{\partial \ell}{\partial l_y} = 0 \Leftrightarrow u_e' \left( x + \int_0^\theta l_y(\theta) \, d\theta \right) = c_y(\theta) + \pi(\theta) - \gamma_y(\theta),
$$

$$
(2a)
$$

$$
\pi(\theta) \geq 0, \quad \pi(\theta)[g(\theta) - l_f(\theta) - l_y(\theta)] = 0
$$

$$
(6a)
$$

along with the associated Kuhn–Tucker conditions for $l_f(\theta)$ and $l_y(\theta)$. Without
solving this model explicitly, we can obtain several insights. Suppose $\hat{\theta} \in (0, \hat{\theta})$ is the
lowest quality land exploited at any instant. Then some land is fallow and rent is zero
on the marginal quality land. However, intramarginal rent for qualities $\theta < \hat{\theta}$ will be
positive. These lands will specialize in either food or clean energy production. One
may expect that when energy prices are low at the initial stage, lower quality lands
may be used for energy. However, as the price of energy rises because of scarcity,
energy production may shift to higher quality lands and more of the food production
may move to lower quality lands. There may be multiple land qualities assigned to
food or energy production. The precise nature of land allocation depends on the
shape of the land rent functions under each use. Both extensive and intensive land margins will be affected by increasing scarcity of the fossil fuel. Without further characterization of the quality-dependent cost functions, it is hard to predict how environmental regulation will affect the allocation of land by quality.\(^{18}\)

5.4. A damage function for pollution

It is important to examine how the model results may be affected with a more general damage function for pollution. Let us consider a general function as in Farzin (1996), in which damages from pollution are a function both of the stock of pollution and the net flow of pollution. We define

\[
Z(t) = x(t) - zZ(t) = z(t),
\]

where \(z(t)\) is the flow of pollution which equals emissions from burning of the fossil fuel net the natural dilution. Then as in Farzin (1996), damages from pollution are defined as \(D(z(t), Z(t))\), with \(D_1 > 0, D_2 > 0\), \(D_{11} \geq 0, D_{22} \geq 0, D_{12} \geq 0\). Marginal damages from each argument increase at a decreasing rate and the two factors may have a synergistic effect. With no environmental regulation, the modified necessary condition \((3)\) becomes

\[
\frac{\partial \ell}{\partial x} = 0 \Leftrightarrow \mu' = c_x + \lambda + D_1 - \gamma_x
\]

together with the new equation of motion for the costate variable \(\mu(t)\) given by

\[
\dot{\mu} = \rho \mu - \frac{\partial \ell}{\partial Z} \Leftrightarrow \dot{\mu} = \mu(\rho + z) + D_2,
\]

and \((9)\) is no longer valid since there is no ceiling on the pollution stock. Comparing \((3)\) and \((3b)\), note that instead of the negative shadow price of pollution \(\mu(t)\) we now have the positive marginal damage from the net flow of pollution \(\partial D/\partial z\). Both terms increase the real cost of resource extraction. With an explicit damage function, it is not just the future cost of environmental regulation that affects current extraction, but the marginal damage from the net emission of pollution. Another important difference is in the growth of the shadow price of the externality over time given by \((8b)\). There is now an extra term, given by the marginal damage from the stock which increases the rate of growth of the shadow price of the externality. In the special case of a ceiling the marginal damage is exactly the value of the multiplier \(v\) when the ceiling is constrained. It is clear that even in the model with only a ceiling and no marginal damages at lower levels of pollution, there will be a positive externality cost from the very beginning of the planning period. In fact it is easy to see that Farzin’s (1996) Proposition 3 holds in the special case when there are no environmental damages but a threshold level of pollution stock binds over some interval in the future.

\(^{18}\)An alternative way of modeling land quality is to assume that land produces just one type of grain, which can then be transformed into either food or energy at constant average cost. Then the unit cost of food or clean energy may be written as \(c_i(\theta) = c_{qi}(\theta) + c_i\), \(i \in \{f, y\}\) where \(c_{qi}(\theta)\) is the unit cost of grain production on land of quality \(\theta\) and \(c_i\) is the transformation cost of grain into final product \(i\).
5.5. Regulation of pollution flows instead of stocks

An alternative way of modeling environmental regulation is through a constraint on the flow of pollution. Several authors have argued that the emission limits under the Kyoto Protocol may be thought of as a constraint on the flow and not the stock of pollution. For example, this could be imposed as an exogenous limit on the extraction rate, as has been done by Smulders and Van der Werf (2005). Let the ceiling on the extraction rate of the nonrenewable resource be given by \( \dot{x} \). Then we can impose a constraint of the form \( x(t) \leq \dot{x} \). Suppose the associated multiplier is denoted by \( \eta \). We have the corresponding necessary condition

\[
\frac{\partial \ell}{\partial x} = 0 \Leftrightarrow u'_e(x + y) = c_x + \dot{x} + \eta - \gamma_x
\]  

(3c)

and \( \eta(\dot{x} - x) \geq 0 \). How will the solution change if regulation is in the form of a flow constraint? Because of Hotelling, the price of the nonrenewable resource must increase over time. Thus the extraction rate will decrease. Therefore depending upon the abundance of the resource relative to energy demand, it is possible that over an initial period, the extraction rate is constrained at \( \dot{x} \) and emissions are at their maximum allowable. However, once the price of the resource is sufficiently high, the constraint will no longer be binding and extraction will be dictated by scarcity alone.\(^{19,20}\)

6. Concluding remarks

In this paper we develop a Hotelling model with a market for land that drives the supply of clean energy. We discover a range of energy prices within which the land-based fuel may substitute for the fossil fuel. Regulation causes the price of energy to increase, therefore more land is allocated away from food production. This leads to a reduction in the food supply and an increase in the price of food. Depending on whether land is abundant and the relative magnitude of demands for food and energy, the supply of the land fuel may exhibit multiple discontinuities, and may

\(^{19}\)There are other possible extensions of the model that can be considered in later research. For example, food and energy may be complements \( (U_{fe} > 0) \) if the process of food consumption requires energy, as in purchasing, processing, cooking, etc. Then rising energy prices will imply lower food prices and increased substitution of the land-based fuel. They may be substitutes \( (U_{fe} < 0) \) if food is a source of energy, such as walking or biking instead of driving in transportation. In this case, substitution of land away from food to the clean fuel may be less extensive.

\(^{20}\)Yet another interesting possibility raised by an anonymous referee is when the starting value of the stock of pollution is higher than the target level \( \bar{Z} \). This could happen if there is a downward correction in the target level because of say, new scientific knowledge about damages. Then the optimal policy may involve a period when only the land-based fuel is utilized with no fossil fuel extraction. Because of atmospheric dilution, the stock of carbon will steadily reduce to the regulated level \( \bar{Z} \). Beyond this point if demand is high, both energy sources may be used. Or if demand is low, only the fossil fuel may be used for a period of time. The optimization problem \( (P) \) will need to be rewritten to accommodate this case since the constraint \( \bar{Z} - Z \geq 0 \) is violated during an initial period.

occur before or after environmental regulation is binding. A ceiling on the stock of pollution forces food production and prices to remain constant over an extended time period, albeit at a higher level than under no regulation.

The proposed framework can be used to make informed predictions on how agricultural policies may affect the supply of clean energy from land that substitutes for polluting resources such as oil in transportation. Policies that decrease the demand for food may increase the supply of the clean energy. These may include the removal of export subsidies on the domestic agricultural sector and import tariffs for agricultural products. Technological change in food production (e.g., introduction of high-yielding varieties) that increase profits per unit of land will lead to a substitution of land away from energy into food production and a consequent increase in the price of energy. In the other direction, environmental policies in the energy sector may affect the land market equilibrium. For instance, stricter limits on carbon concentration will mean a tighter ceiling constraint, and lower extraction rates of fossil-based energy. This in turn implies an increase in the production of agricultural fuels and lower food supplies. At a country level, this may mean increased food imports by countries that have stricter environmental policies. For example, environmental regulation in developed economies may lead to increased imports from developing countries. Domestically, there may be a shift in land use from other sectors into the production of food and energy.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jedc.2007.04.009.

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