

Pricing the ecosystem and taxing ecosystem services: a general equilibrium approach

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Abstract

In an integrated dynamic general equilibrium model of the economy and the ecosystem humans and wildlife species compete for land and prey biomass. We introduce a competitive allocation mechanism in both submodels such that economic prices and ecosystem prices guide the allocation in the economy and in the ecosystem, respectively. It is shown that efficiency restoring resource policies need to account for ecosystem prices and that economic prices for land and biomass, respectively, exceed their ecosystem counterpart.

JEL classification: H21, Q28

Key words: land, biomass, ecosystem services

1 The problem

Despite our rich knowledge of significant and large-scale interdependencies between the ecosystem and the economy (Alcamo et al., 2003), many pertaining environmental-economic studies tend to be somewhat unbalanced by offering an elaborate analysis of economic activities and far less elaborate modeling of the ecosystem and ecological feedback effects. To the extent that such studies "... do merge economic and ecosystem concepts [they] tend to address isolated markets and a very few species" (Tschirhart, 2000, p. 13). Such approaches offer limited insights only in the complex impacts on the ecosystem of human activities such as land conversion for economic use or biomass harvesting. These economic activities have ramifications and trigger adaptations in the ecosystem and eventually adversely affect ecosystem services that support human lives.

In his state-of-the-art survey Brown (2000) emphasizes that renewable natural resources are embedded in complex technological interdependencies of ecosystems and that their allocation is characterized by an "... interplay of poorly defined property rights, externalities and market failure" (p. 875). He also observes that economic models rarely extend resource interdependence beyond one or two natural resources (similar: Deacon et al. 1998) and he criticizes the propensity of economists to treat their oversimplified resource models as more than a metaphor when they offer policy advice, e.g. based on an optimal single species solution that ignores predator-prey interactions and other ecosystem interdependencies. Among Brown's (2000) prime research desiderata are increased efforts to better understand the role and function of ecosystems as well as the need to better integrate economics and ecology. Similar programmatic statements have been made by Finnoff and Tschirhart (2003a, p. 590).

While economists have a good understanding of the resource allocation mechanism in market economies by applying the *economic* concept of general competitive equilibrium analysis¹ we are not aware of a comparable approach to the ecosystem that would be, at the same time, a suitable microfounded building block for a truly general dynamic equilibrium analysis encompassing the economy and the ecosystem as its interdependent subsystems.² To cope with major interdependencies and feedback effects within and between the ecosystem and the economy, we suggest such an integrated general equilibrium analysis that encompasses both subsystems, the ecosystem and the economy, and treats both at the same level of analytical complexity. We address the dynamic allocation of land and non-human biomass with a major focus on the ecosystem model and its links to the economic

¹For general equilibrium analyses applied in environmental economics we refer to Mäler (1974), Bovenberg and de Mooij (1994), Bovenberg and Goulder (1996) or Fullerton and Wolverton (2005).

²For dynamic ecological economic analyses along other lines see e.g. van den Bergh and Nijkamp (1991).

submodel. Economic methodology is used to explain the interaction of species building on a small but growing literature.

Hannon (1976) formalized the notion and some implications of individual organisms optimizing net energy. Tschirhart (2000) treats such organisms as firms and is the first, to our knowledge, who models the ecosystem with optimizing individuals in a general equilibrium framework. Organisms incur energy costs, when preying biomass or sacrificing own biomass, and these transactions costs change endogenously as to equilibrate all predators' prey biomass and all preys' loss of own biomass. Finnoff and Tschirhart (2003a, 2003b) demonstrate the capacity of that approach to tackle harvesting with complex intra-ecosystem interactions in numerical applied analysis. Eichner and Pethig (2005) take up Tschirhart's concept of general equilibrium in an integrated ecological-economic system (IEES). They replace the concept of equilibrating transaction costs by a complete system of competitive ecosystem markets and show that individual organisms can be interpreted as price-taking profit-maximizing firms under the control of a big artificial 'agricultural firm' (biomass firm). Christiaans et al. (2006) model the ecosystem in isolation and determine the resource allocation in that system with the help of the competitive mechanism treating individual organisms analogous to price-taking consumers who maximize net offspring under some transactions constraints. They show that the competitive allocation mechanism, a proven powerful method of dealing with interdependencies in market economies, can be fruitfully applied to model the intertemporal allocation in the ecosystem.

In the present paper we take up the approach of Christiaans et al. (2006) to the resource allocation in the ecosystem and link the ecosystem and the economy as interdependent subsystems in an integrated ecological-economic system where both subsystems are microfounded and treated at the same level of structural detail: individual agents optimize subject to constraints and competitive markets provide for the compatibility of individual actions (plans).³ In this setup we then focus on public consumptive ecosystem services provided by the ecosystem, biomass harvested by humans, and land converted for economic use. In our setup humans compete with all species for land and for (nonhuman) biomass, but that competition is grossly unbalanced, since humans are top predators restrained only by their perceived self-interest.

The important feature of the IEES is that in both subsystems all (private) goods and services are traded on perfectly competitive markets. Disturbances - or shocks - in

³Large parts of the ecological and bioeconomic literature focus on macro-level approaches regarding populations as the appropriate units for studying dynamic ecosystem allocations. There are also ecological models that link individual behavior to population processes (e.g. Persson and de Roos, 2003) but we are not aware of an attempt to link such models to an equilibrium model of the economy.

one of the subsystems cause allocative displacement effects and change relative scarcities (prices). The shocks spill over to the other subsystem causing price and quantity feedback effects although the market systems in both submodels are completely disconnected. It is a particularly important aspect of our approach, and an innovative one to our knowledge, that there is a market for land and for prey biomass in each subsystem. Since arbitrage activities between these markets are ruled out, the equilibrium prices in both market segments will not be the same, in general. We know, on the other hand, that homogeneous goods are sold at a uniform price in unsegmented perfectly competitive markets (Jevon's 'law of indifference') and that - subject to some qualifications - uniform prices are a necessary condition for the efficient allocation of homogeneous goods in disconnected competitive markets. To put it differently, the allocation in the IEES is inefficient, unless the prices for biomass and land are as they would be in the (hypothetical) case that the market systems in both submodels were not disconnected.

Not surprisingly, in the absence of corrective nature protection policies, the allocation in the IEES turns out to be inefficient because the economic prices for biomass and land do not properly reflect the scarcity of these commodities in the ecosystem. It is shown that the regulator can restore efficiency by imposing a tax on harvested biomass and on economic land equal to, or encompassing, the ecosystem price of the respective good. Moreover, for efficient steady states we are able to determine the total value of all species, the total value of the ecosystem and the value of the entire stock of land.

Section 2 outlines the model and section 3 introduces the concept of a competitive general equilibrium of the IEES. The main results on the (in)efficiency of such general equilibria are presented in section 4 with special emphasis on the prices of land and biomass in both submodels. Section 5 concludes.

2 The model

Consider a *non-biomass natural resource* whose stock $\bar{r} \in \mathbb{R}_{++}$ is time-invariant and the use of which is essential for both humans and nonhuman species. We will refer to that resource as land because land appears to be a well fitting and very important example.⁴ To simplify, the use of land is assumed to be exclusive in the sense that nonhuman species (species, for short) cannot live on land used for economic purposes, and land used by species is off limits for humans. The land used by humans, $r \in [0, \bar{r}]$ is called *economic land*, for short, and the land used by species, $\bar{r} - r =: s$ is called *habitat*. The supply of economic land is expanded

⁴At the expense of some stylization, other examples are water basins, water courses or air sheds.

or reduced over time according to⁵

$$\dot{r} = R \begin{pmatrix} r, \mathbf{y}_r \\ - \\ + \end{pmatrix}, \quad (1)$$

where $\mathbf{y}_r^\top := (y_{r1}, \dots, y_{r\bar{g}}) \in \mathbb{R}_+^{\bar{g}}$ denotes the vector of \bar{g} (private) inputs used for maintenance and development of economic land. (1) is interpreted as the technology of a land converting firm. By definition of s the habitat changes over time according to

$$\dot{s} = -\dot{r} = -R(r, \mathbf{y}_r). \quad (2)$$

The habitat s is home of \bar{i} species whose populations are denoted by $\mathbf{n}^\top := (n_1, \dots, n_{\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$. Individual *organisms* belonging to the same species are identical. The representative individual of species i , called organism i for short, generates net offspring

$$b_i = B^i \begin{pmatrix} s_i, \mathbf{z}_i \\ + \\ + \end{pmatrix} \quad i = 1, \dots, \bar{i} \quad (3)$$

at each point in time. In (3) $s_i \in \mathbb{R}_+$ denotes organism i 's exclusive use of land services. For example, plants occupy a patch of land that gives them (limited) access to sunlight, fresh water and nutrients. The supply of these services is supposed to equal the size of the patch occupied by the organism.⁶

The vector $\mathbf{z}_i^\top := (z_{i1}, \dots, z_{ii}, \dots, z_{i\bar{i}}) \in \mathbb{R}^{\bar{i}}$ contains all biomass transactions of organism i . For $i \neq j$, z_{ij} is organism i 's intake of (or in economic terms: organism i 's demand for) biomass of its prey species j , and z_{ii} is organism i 's loss (or supply) of own biomass to its predators. The sign convention is $z_{ij} \geq 0$ for $i \neq j$ and $z_{ii} \leq 0$.

By definition of b_i and n_i the population growth turns out to be

$$\dot{n}_i = n_i b_i \quad i = 1, \dots, \bar{i}. \quad (4)$$

Being the top predators in the IEES, humans compete with nonhuman species for prey biomass. Let $h_i \geq 0$ be the biomass of species i harvested by humans. h_i is the output of the harvesting (production) function

$$h_i = H^i \begin{pmatrix} n_i, \mathbf{y}_i \\ + \\ + \end{pmatrix} \quad i = 1, \dots, \bar{i}, \quad (5)$$

⁵Upper case letters denote functions and subscripts attached to them indicate first derivatives. A plus or minus sign underneath an argument denotes the sign of the respective partial derivative.

⁶This setup describes land used by plants quite well but mobile animals use land in different ways. Although their land use could be modeled by introducing land services as (congestible) public goods, we refrain from that extension to keep the exposition simple.

where $\mathbf{y}_i^\top := (y_{i1}, \dots, y_{i\bar{g}}) \in \mathbb{R}_+^{\bar{g}}$ are harvesting inputs and where $H_{n_i}^i > 0$ is the population stock externality known from classical harvesting models. Economic goods and services are supplied by a representative production firm using the technology

$$F(\mathbf{h}_f, r_f, \mathbf{y}_f) \geq 0, \quad (6)$$

where $r_f \in \mathbb{R}_+$ is the input of economic land services, $\mathbf{h}_f^\top := (h_{f1}, \dots, h_{f\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$ is the input of harvested biomass and where $\mathbf{y}_f^\top := (y_{f1}, \dots, y_{f\bar{g}}) \in \mathbb{R}^{\bar{g}}$ is the input-output vector of goods and services. The sign convention is that g is an output, if $y_{fg} > 0$, and an input, if $y_{fg} < 0$.

The human population of consumers is time-invariant. With all consumers being identical it suffices to consider a representative consumer whose utility is

$$u = U(\mathbf{q}_c, \mathbf{y}_c), \quad (7)$$

where $\mathbf{q}_c^\top := (q_{c1}, \dots, q_{c\bar{k}}) \in \mathbb{R}^{\bar{k}}$ is a vector of public ecosystem services⁷ and $\mathbf{y}_c^\top := (y_{c1}, \dots, y_{c\bar{g}}) \in \mathbb{R}^{\bar{g}}$ is a vector of goods and services such that y_{cg} is a (private) good or service for consumption, if $y_{cg} > 0$, and it is a labor service supplied by the consumer, if $y_{cg} < 0$. The ecosystem services are supplied by the ecosystem according to the function⁸

$$\mathbf{q} = \mathbf{Q} \left(\begin{matrix} \mathbf{n}, r \\ +, - \end{matrix} \right) = \left[Q^1(\mathbf{n}, r), \dots, Q^{\bar{k}}(\mathbf{n}, r) \right]. \quad (8)$$

The IEES is closed with the help of the following resource constraints:

$$\mathbf{y}_f \geq \mathbf{y}_c + \sum_i \mathbf{y}_i + \mathbf{y}_r, \quad (9)$$

$$\mathbf{q} \geq \mathbf{q}_c, \quad (10)$$

$$\mathbf{h} \geq \mathbf{h}_f, \quad (11)$$

$$r \geq r_f, \quad (12)$$

$$\bar{r} - r \geq \sum_i n_i r_i, \quad (13)$$

$$\sum_j n_j z_{ji} + h_i = 0 \quad i = 1, \dots, \bar{i}, \quad (14)$$

⁷The ecosystem services considered here "... are not traded or valued in the marketplace ... [and] ... serve as public good rather than provide direct benefits to individual land owners" (Daily et al. 1997, p. 13). The consumption of these ecosystem services can alternatively be interpreted as the nonconsumptive use of renewable resources whose economic value may be substantial (Brown, 2000, p. 887).

⁸ $Q_r < 0$ in (8) because according to Daily et al. (1997) relatively undisturbed land sustains the delivery of essential ecosystem services. Albers (1996) argues that preserved land can provide to neighboring economic land various benefits such as local climate effects, recreation, emission control or an enhanced view.

where $\mathbf{h} := (h_1, \dots, h_{\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$. The resource constraint (9) is similar to that in conventional Debreu-type general equilibrium models of the economy where it is, in fact, the only resource constraint. All other constraints (10) - (14) specify and formalize the fundamental interdependence between the ecosystem and the economy: The inequality (10) forces the economy to be content with whatever ecosystem services \mathbf{q} are provided by the ecosystem. The inequalities (11) and (12) constrain the economic demand for the ecosystem goods biomass and land to the amount of biomass harvested and to the land converted, respectively. The inequality (13) and the equation (14) force the nonhuman species to accommodate to the economic land use and biomass predation, respectively. (13) - (14) reflect the iron rule of the IEES, that all nonhuman species have to contend themselves with what is left after humans have set apart land and biomass for their own use.

We refrain from modeling durable human-made capital goods, capital formation and pollution since these additional features would severely raise the complexity of the analysis without providing new insights.

3 The allocation mechanism: Competitive markets in both subsystems

Our description of the competitive market economy can be very brief since that concept is standard in economics. There are markets for all commodities, for the biomass harvested, and for economic land. The corresponding market prices are $\mathbf{p}_y^\top := (p_{y1}, \dots, p_{y\bar{g}}) \in \mathbb{R}_+^{\bar{g}}$, $\mathbf{p}_h^\top := (p_{h1}, \dots, p_{h\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$ and $p_r \in \mathbb{R}_+$. Although we postpone the discussion of nature protection to Section 4, it is convenient to introduce here already taxes on harvested biomass, $\boldsymbol{\theta}_h^\top := (\theta_{h1}, \dots, \theta_{h\bar{i}}) \in \mathbb{R}^{\bar{i}}$, and on economic land, $\theta_r \in \mathbb{R}$. For notational relief, we write $\mathbf{p} := (\mathbf{p}_h, p_r, \mathbf{p}_y)$, $\boldsymbol{\theta} := (\boldsymbol{\theta}_h, \theta_r)$, and we denote by \mathbf{K} the function describing an entire time path of the (possibly multidimensional) variable \mathbf{k} . In other words, the functional sign \mathbf{K} is supposed to convey the information $\mathbf{k}_t = \mathbf{K}(t)$ for all $t \in [0, \infty[$. For example, $\mathbf{P} = (\mathbf{P}^h, \mathbf{P}^r, \mathbf{P}^y)$ describes specific time paths of prices $\mathbf{p}_t := (\mathbf{p}_{ht}, p_{rt}, \mathbf{p}_{yt})$ such that $\mathbf{p}_t = \mathbf{P}(t)$, $\mathbf{p}_{ht} = \mathbf{P}^h(t)$, $p_{rt} = \mathbf{P}^r(t)$ and $\mathbf{p}_{yt} = \mathbf{P}^y(t)$.⁹ With this notation the optimal plans of the economic agents are specified as follows:

- For given \mathbf{P} , $\boldsymbol{\Theta}^r$ and an initial stock of economic land, r_0 , the land conversion firm

⁹Putting up with a slight misuse of notation in favor of simplicity we will denote by \mathbf{R} , \mathbf{H} and \mathbf{Q} the functions determining time paths of converted land, harvested biomass and ecosystem services, respectively, although these functions differ from the functions R , H^i and \mathbf{Q} in (1), (5) and (8).

solves:

$$\max_{(\mathbf{Y}^r)} \int_0^\infty e^{-\delta t} [(p_r - \theta_r)r - \mathbf{p}_y^\top \cdot \mathbf{y}_r] dt \quad \text{s.t. (1)}. \quad (15)$$

- For given \mathbf{P} , Θ^h and \mathbf{N} the harvesting firm solves

$$\max_{(\mathbf{H}, \mathbf{Y}^1, \dots, \mathbf{Y}^i)} \int_0^\infty e^{-\delta t} \sum_i [(p_{hi} - \theta_{hi})h_i - \mathbf{p}_y^\top \cdot \mathbf{y}_i] dt \quad \text{s.t. (5)}. \quad (16)$$

- For given \mathbf{P} the production firm solves

$$\max_{(\mathbf{H}^f, \mathbf{R}^f, \mathbf{Y}^f)} \int_0^\infty e^{-\delta t} [\mathbf{p}_y^\top \cdot \mathbf{y}_f - \mathbf{p}_h^\top \cdot \mathbf{h}_f - p_r r_f] dt \quad \text{s.t. (6)}. \quad (17)$$

- For given \mathbf{P} and \mathbf{Q} the representative consumer solves

$$\max_{(\mathbf{Y}^c)} \int_0^\infty e^{-\delta t} U(\mathbf{q}_c, \mathbf{y}_c) dt \quad \text{s.t. } \mathbf{p}_y^\top \cdot \mathbf{y}_c \leq w, \quad (18)$$

where w are lumpsum payments of profits and government transfers treated as constant by the consumers.

In (15) - (18) all agents are modeled as (non-myopic) dynamic optimizers although the conversion firm is the only agent whose intertemporal plan is non-trivial. Our implicit assumption is that biomass in situ and land available for conversion (i.e. the habitat) are free goods because instantaneous demand falls short of total supply at a price that covers at least marginal costs of harvesting and land conversion, respectively.¹⁰ As a consequence the habitat and in situ biomass are free access common property resources which are therefore appropriated for free by the land converting firm and the harvesting firm. Nonetheless, these firms will sell their output to the production firm at a positive price to cover their marginal costs.¹¹

Note also that all economic agents' plans (15) - (18) are directly or indirectly linked to ecological variables: The land converting firm and the harvesting firm take land and biomass, respectively, from nonhuman species; the production firm transforms economic land and harvested biomass into consumer goods; and consumers rely on ecosystem services.

¹⁰The explicit introduction of exclusive property rights for land would not matter as long as the habitat is worthless for the owner. Property rights to the biomass in situ do not matter, either, if it is assumed that due to the complexities of ecosystem interdependencies no owner would be able to calculate her profit-maximizing intertemporal harvesting plan. If there are owners they are implicitly assumed to be ignorant with respect to future prices and populations and hence behave myopically in that regard.

¹¹One can easily verify that if there were no costs of harvesting and land conversion and no corrective regulation, myopic economic agents would destroy the habitat and all nonhuman species.

Having completed the description of the market economy we now define the competitive general *economic equilibrium*:

For any given time paths of ecosystem services, \mathbf{Q} , species populations, \mathbf{N} and taxes Θ a general economic equilibrium is constituted by prices \mathbf{P} and by an economic allocation $\mathbf{A}^y := (\mathbf{H}, \mathbf{H}^f, \mathbf{R}, \mathbf{R}^f, \mathbf{Y}^c, \mathbf{Y}^f, \mathbf{Y}^r, \mathbf{Y}^1, \dots, \mathbf{Y}^{\bar{i}})$ such that

- the solutions to the optimization programs (15) - (18) for \mathbf{Q} , \mathbf{N} and Θ coincide with \mathbf{A}^y and
- the resource constraints (10) - (12) are satisfied.

The general economic equilibrium is a state where all markets are cleared at each point in time and where no price-taking agent is able to improve upon their well-being as specified by their respective objective functions. From the perspective of the IEES, this equilibrium is partial, however, since it is conditional on predetermined \mathbf{Q} , \mathbf{N} and Θ . The economic activities of land use and harvesting implied by that economic equilibrium may not be consistent with the *given* time paths \mathbf{Q} , \mathbf{N} and Θ on which that equilibrium has been conditioned.

To tackle that consistency issue we need to specify the allocation mechanism in the ecosystem. Following Christiaans et al. (2006) we assume that at each point in time the allocation of land and biomasses is determined in the ecosystem by a mechanism that works as if these goods were traded on competitive markets by all organisms which are supposed to behave as if they maximize their net offspring subject to some transactions constraint. More specifically, denote by $\pi_s \in \mathbb{R}_+$ the ecosystem price of land and by $\boldsymbol{\pi}_z^\top := (\pi_{z1}, \dots, \pi_{z\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$ the ecosystem prices for all species' biomass.¹² For given $\boldsymbol{\Pi} := (\boldsymbol{\Pi}^z, \boldsymbol{\Pi}^s)$, \mathbf{H} and \mathbf{R} , and at each point in time organism $i = 1, \dots, \bar{i}$ solves

$$\max_{(s_i, \mathbf{z}_i)} B^i(s_i, \mathbf{z}_i) \quad \text{s.t.} \quad \pi_s(\omega_i - s_i) \geq \boldsymbol{\pi}_z^\top \cdot (\mathbf{z}_i + \mathbf{h}_i), \quad (19)$$

where $\mathbf{h}_i := (h_{i1}, \dots, h_{ij}, \dots, h_{i\bar{i}}) \in \mathbb{R}_+^{\bar{i}}$ with $h_{ij} \equiv 0$ for $i \neq j$ and $h_{ii} \equiv h_i/n_i$ and where

$$\omega_i = \omega_i(s, \mathbf{n}) := \frac{\sigma_i s}{\sum_j \sigma_j n_j} \in \mathbb{R}_+ \quad (20)$$

is organism i 's endowment or entitlement to land services. In (20), $(\sigma_1, \dots, \sigma_{\bar{i}})^\top \in \mathbb{R}_+^{\bar{i}}$ is a set of constant weights indicating the species' rank - or predation power - within the

¹²These prices are meant to be scarcity indicators as perceived by the organisms. To avoid clumsy wording we call them prices, nonetheless, and refer to 'ecosystem markets' although there exist neither a currency nor institutionalized markets in the ecosystem. Interestingly, these features are also missing in the standard general equilibrium model of the neoclassical economy.

community of species. By definition of $\omega_i(\cdot)$ it is true that $\sum_j n_j \omega_j(\cdot) = s$ which gives rise to the interesting interpretation that the habitat is owned by all organisms.¹³

In this setup, we now define a competitive general *ecological equilibrium* as follows:
For any given time paths of human biomass harvesting, \mathbf{H} , and economic land use, \mathbf{R} , a general ecological equilibrium is constituted by prices $\mathbf{\Pi}$ and an ecological allocation $\mathbf{A}^m := (\mathbf{S}^1, \dots, \mathbf{S}^i, \mathbf{Z}^1, \dots, \mathbf{Z}^i, \mathbf{Q}, \mathbf{N})$ such that the solutions to all instantaneous optimization programs (19) for \mathbf{H} and \mathbf{R} coincide with \mathbf{A}^m .

The general ecological equilibrium is a state where all ecosystem markets clear at each point in time and where no price-taking organism is able to increase its net offspring. To show in a more explicit way that the general ecological equilibrium consists of a sequence of short-run (or rather: instantaneous) equilibria recall that at each point in time some vector $\mathbf{v} := (\mathbf{h}, \mathbf{n}, r)$ is given. Denote by $\tilde{S}^i(\boldsymbol{\pi}, \mathbf{v})$ and $\tilde{Z}^i(\boldsymbol{\pi}, \mathbf{v})$ organism i 's demands and supplies determined by solving (18) when prices are $\boldsymbol{\pi} := (\pi_s, \boldsymbol{\pi}_z)$. Invoke (13) and (14) and solve the equations

$$s = \sum_i n_i \tilde{S}^i(\boldsymbol{\pi}^*, \mathbf{v}) \quad \text{and} \quad \sum_j n_j \tilde{Z}^{ji}(\boldsymbol{\pi}^*, \mathbf{v}) + h_i = 0 \quad (\text{all } i)$$

for the ecosystem prices $\boldsymbol{\pi}^*$. These prices $\boldsymbol{\pi}^*$ clearly depend on \mathbf{v} and we therefore obtain the short-run equilibrium demands and supplies as functions of \mathbf{v} , say $S^i(\mathbf{v})$ and $\mathbf{Z}^i(\mathbf{v})$, which determine the equilibrium net offspring $B^i[S^i(\mathbf{v}), \mathbf{Z}^i(\mathbf{v})]$, in turn. When the equilibrium net offspring is combined with (4) we obtain the system of population growth functions¹⁴

$$\dot{n}_i = n_i B^i[S^i(\mathbf{v}), \mathbf{Z}^i(\mathbf{v})] = N^i(\mathbf{h}, \mathbf{n}, r) \quad (\text{all } i). \quad (21)$$

We have thus demonstrated that for given \mathbf{H} and \mathbf{R} the time path of ecological equilibrium allocations, \mathbf{A}^m , fully determines the development of all populations over time: $\mathbf{N} = (\mathbf{N}^1, \dots, \mathbf{N}^i)$.

Although the ecological equilibrium defined above is a general equilibrium for pre-determined \mathbf{H} and \mathbf{R} , it constitutes a partial equilibrium from the perspective of the IEES

¹³See also Christiaans et al. (2006). Note, however, that organism i 's income from its entitlement to land services, $\pi_s \omega_i(s, \mathbf{n})$, is subject to endogenous price changes while in Christiaans et al. (2006) that income is assumed to be 'exogenous' (implying that the pertinent functions of biomass supply and demand are not homogeneous of degree zero in prices). In analogy to the economic theory of the household, organism i receives the 'biomass income' $|\pi_{z_i} z_{ii}|$ in addition to its income $\pi_s \omega_i(s, \mathbf{n})$ but it loses the amount $\pi_{z_i} h_i / n_i$ of the former to the humans without compensation.

¹⁴Classical bioeconomic harvesting models typically assume rather than derive population growth functions of the type $\dot{n}_i = \hat{N}^i(\mathbf{n}) - h_i$ for all i . The functions N^i in (21) differ from the functions \hat{N}^i in several important aspects: $N_{h_i}^i < 0$ but $N_{h_i}^i \neq -1$ (in general) versus $\hat{N}_{h_i}^i = -1$; $N_{h_j}^i \neq 0$ (in general) versus $\hat{N}_{h_j}^i = 0$; $N_r^i > 0$ (in general) versus $\hat{N}_r^i = 0$.

since its links to the economic submodel have artificially been set constant. In other words, so far we have introduced the concept of general equilibrium for each subsystem. Yet these subsystem equilibria are conditioned on variables determined in the other subsystem. The concept of competitive general equilibrium of the (entire) IEES needs to account for these interdependencies:

For any predetermined time path of taxes, Θ (including the case $\Theta(t) = 0$ for all t) a general equilibrium of the IEES, $[(\mathbf{P}^, \mathbf{A}^{y*}, \Theta), (\mathbf{\Pi}^*, \mathbf{A}^{m*})]$, prevails, if $(\mathbf{P}^*, \mathbf{A}^{y*}, \Theta)$ is a general economic equilibrium relative to \mathbf{Q}^* and \mathbf{N}^* and if $(\mathbf{\Pi}^*, \mathbf{A}^{m*})$ is a general ecosystem equilibrium relative to \mathbf{H}^* and \mathbf{R}^* .*

To better understand the structure of the general equilibrium of the IEES consider a fancy hybrid Cournot-Nash game of two Walrasian auctioneers one for each submodel. For given Θ their strategies are $(\mathbf{P}, \mathbf{A}^y)$ and $(\mathbf{\Pi}, \mathbf{A}^m)$, respectively, and they attain their maximum payoff by choosing market-clearing prices in their respective submodel. Although we do not intend to formalize this 'super game' we find it useful because it highlights the existence of different and disconnected price mechanisms (reflecting decentralized decision making) in both subsystems.

4 Allocative efficiency in the IEES

To explore the efficiency properties of a general equilibrium of the IEES, consider as a benchmark the socially optimal allocation determined by a social planner who solves the optimal control problem:

$$\max \int_0^\infty e^{-\delta t} U(\mathbf{q}_c, \mathbf{y}_c) dt \quad \text{s.t. (1) - (14).}$$

We write down the Hamiltonian associated to that complex control problem for the purpose of keeping track of the Lagrange multipliers and co-state variables:

$$\begin{aligned} \mathcal{L}^P &= U(\mathbf{q}_c, \mathbf{y}_c) + \sum_i \beta_i n_i B^i(s_i, \mathbf{z}_i) + (\rho - \gamma)R(r, \mathbf{y}_r) + \alpha_f F(\mathbf{h}_f, r_f, \mathbf{y}_f) \\ &+ \sum_k \alpha_{qk} [Q^k(\mathbf{n}, r) - q_k] + \sum_i \alpha_{hi} [H^i(n_i, \mathbf{y}_i) - h_i] + \sum_k \alpha_{qk}^c (q_k - q_{ck}) \\ &+ \sum_g \alpha_{yg} \left(y_{fg} - y_{rg} - \sum_i y_{ig} - y_{cg} \right) - \sum_i \alpha_{zi} \left(\sum_j n_j z_{ji} + h_i \right) \\ &+ \sum_i \alpha_{vi} (h_i - h_{fi}) + \alpha_r (r - r_f) + \alpha_s \left(s - \sum_i n_i s_i \right). \end{aligned} \quad (22)$$

The relevant implications of the first-order conditions of solving (22) are listed in the first column of Table 1.^{15,16} The existence issue is answered in¹⁷

Proposition 1.

If the functions B^i , F , H^i , Q^k , R are quasi-concave, a solution $(\alpha, \beta, \gamma, \rho, \mathbf{A}^m, \mathbf{A}^y)$ to the Hamiltonian (22) exists.

Necessary conditions for a		
No.	social optimum	general equilibrium
1	$\frac{R_{yrg}}{R_{yr1}} = \frac{\alpha_{yg}}{\alpha_{y1}}$ all g	$\frac{R_{yrg}}{R_{yr1}} = \frac{p_{yg}}{p_{y1}}$ all g
2	$\alpha_{vi} = \frac{\alpha_{yg}}{H_{yig}^i} + \alpha_{zi}$ all i , any g	$p_{hi} = \frac{p_{yg}}{H_{yig}^i} + \theta_{hi}$ all i , any g
3	$\frac{H_{yig}^i}{H_{yi1}^i} = \frac{\alpha_{yg}}{\alpha_{y1}}$ all i , all g	$\frac{H_{yig}^i}{H_{yi1}^i} = \frac{p_{yg}}{p_{y1}}$ all i , all g
4	$\frac{F_{hfi}}{F_{yf1}} = \frac{\alpha_{vi}}{\alpha_{y1}}$ all i	$\frac{F_{hfi}}{F_{yf1}} = \frac{p_{hi}}{p_{y1}}$ all i
5	$\frac{F_{rf}}{F_{yf1}} = \frac{\alpha_r}{\alpha_{y1}}$	$\frac{F_{rf}}{F_{yf1}} = \frac{p_r}{p_{y1}}$
6	$\frac{U_{ycg}}{U_{yc1}} = \frac{\alpha_{yg}}{\alpha_{y1}}$ all g	$\frac{U_{ycg}}{U_{yc1}} = \frac{p_{yg}}{p_{y1}}$ all g
7	$\frac{B_{zij}^i}{B_{zi1}^i} = \frac{\alpha_{zj}}{\alpha_{z1}}$ all i , all j	$\frac{B_{zij}^i}{B_{zi1}^i} = \frac{\pi_{zj}}{\pi_{z1}}$ all i , all j
8	$\frac{B_{si}^i}{B_{zi1}^i} = \frac{\alpha_s}{\alpha_{z1}}$ all i	$\frac{B_{si}^i}{B_{zi1}^i} = \frac{\pi_s}{\pi_{z1}}$ all i
9	$\dot{\rho} - \dot{\gamma} = (\rho - \gamma)(\delta - R_r) - \alpha_r - \sum_k U_{qck} Q_r^k + \alpha_s,$ $\rho - \gamma = \frac{\alpha_{yg}}{R_{yrg}}$	$\dot{\rho}_r = \rho_r(\delta - R_r) - p_r + \theta_r,$ $\rho_r = \frac{p_{yg}}{R_{yrg}}$
10	$\dot{\beta}_i = \beta_i(\delta - b_i) - \sum_k U_{qck} Q_{ni}^k - \frac{\alpha_{yg} H_{ni}^i}{H_{yig}^i}$ $+ \alpha_s s_i + \sum_i \alpha_{zj} z_{ij}$	—
11	$\frac{U_{qck}}{U_{yc1}} = \frac{\lambda_{qk}^c}{\alpha_{y1}}$ all k	$\frac{U_{qck}}{U_{yc1}} = \frac{\lambda_{qk}}{p_{y1}}$ all k

Table 1: Optimum and equilibrium allocations in the IEES

The next step is to determine the first-order conditions characterizing the general equilibrium of the IEES. The Hamiltonians and Lagrangeans associated to the individual optimization programs (15) - (19) are:

$$\mathcal{L}^r = (p_r - \theta_r)r - \mathbf{p}_y^\top \cdot \mathbf{y}_r + \rho_r R(r, \mathbf{y}_r), \quad (14')$$

$$\mathcal{L}^h = \sum_i [(p_{hi} - \theta_{hi})h_i - \mathbf{p}_y^\top \cdot \mathbf{y}_i] + \sum_i \lambda_{hi} [H^i(n_i, \mathbf{y}_i) - h_i], \quad (15')$$

¹⁵To simplify the exposition we assume in Table 1 that in the solution the variables $y_{r1}, y_{i1}, y_{f1}, y_{c1}$ and z_{i1} (for $i = 1, \dots, \bar{i}$) take on nonzero values for all t . The correct reading of the qualifiers "all i " etc. in Table 1 is that the equation preceding such a qualifier holds for all variables x_i whose solution values are nonzero.

¹⁶The economic interpretation of the efficiency rules listed in Table 1 is left to the reader. For some discussion in a similar context see Eichner and Pethig (2006).

¹⁷The proof of all propositions is delegated to the Appendix.

$$\mathcal{L}^y = \mathbf{p}_y^\top \cdot \mathbf{y}_f - \mathbf{p}_h^\top \cdot \mathbf{h}_f - p_r r_f + \lambda_f F(\mathbf{h}_f, r_f, \mathbf{y}_f), \quad (16')$$

$$\mathcal{L}^c = U(\mathbf{q}_c, \mathbf{y}_c) + \boldsymbol{\lambda}_q^\top \cdot (\mathbf{q} - \mathbf{q}_c) + \lambda_c (w - \mathbf{p}_y^\top \cdot \mathbf{y}_c), \quad (17')$$

$$\mathcal{L}^i = B^i(s_i, \mathbf{z}_i) + \lambda_i [\pi_s (\omega_i - s_i) - \boldsymbol{\pi}_z^\top \cdot (\mathbf{h}_i + \mathbf{z}_i)]. \quad (18')$$

The relevant implications of the first-order conditions of solving (14') - (18') are listed in the second column of Table 1. With that information we now address the question whether an efficient allocation of the IEES can be sustained as a general equilibrium of the IEES supported by suitable taxes.

Our finding is made precise in

Proposition 2.

There exists a solution $(\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\rho}, \mathbf{A}^m, \mathbf{A}^y)$ to the Hamiltonian (22) and a distribution of profit shares and lumpsum transfers to consumers such that $[(\mathbf{P}, \mathbf{A}^y, \boldsymbol{\Theta}), (\boldsymbol{\Pi}, \mathbf{A}^m)]$ is an efficient general equilibrium of the IEES, if and only if for all t prices and tax rates are assigned the values

- $p_{hi} = \alpha_{vi}$ (all i), $p_r = \alpha_r$, $p_{yg} = \alpha_{yg}$ (all g) (economic prices),
- $\pi_{zi} = \alpha_{zi} > 0$ (all i), $\pi_s = \alpha_s$ (ecosystem prices),
- $\theta_r = \pi_s - \sum_k \frac{p_{yg} U_{a_{ck}} Q_r^k}{U_{ycg}} > 0$ (any g), $\theta_{hi} = \pi_{zi} > 0$ (all i) (tax rates) .

Proposition 2 implies that laissez-faire equilibria (defined by $\theta_r = \theta_{hi} \equiv 0$) are inefficient. There are three reasons for this inefficiency: (i) wrong economic price signals for land, (ii) wrong economic price signals for biomass and (iii) a non-internalized ecosystem services externality. Since efficiency requires positive tax rates the economic prices for land and biomass tend to be too low in the laissez-faire regime and therefore economic land and harvested biomass tend to be overprovided.¹⁸ In the case of biomass, the efficient tax rate is a markup on the economic biomass price equal to the ecosystem price of that biomass implying that in laissez-faire economic agents fail to account for the scarcity of biomass in the ecosystem. In the case of land conversion an analogous argument applies but now another markup on economic land is necessary to internalize the ecosystems services externality, $-\sum_k \frac{p_{yg} U_{a_{ck}} Q_r^k}{U_{ycg}}$.

With its specific assignment of prices and tax rates Proposition 2 is a decentralization result in the flavor of the second theorem of welfare economics. Yet Proposition 2 is not a full-blown generalization of that theorem from neoclassical economic models to the IEES for the following reason. The second theorem of welfare economics states, essentially,

¹⁸It is not easy to make this observation rigorous, however, because it compares two different, highly complex general equilibrium allocations.

that every efficient allocation of the economy can be decentralized by prices provided the consumers' endowments and profit shares are specified and consumers receive appropriate redistributive (positive or negative) lumpsum transfers. This lumpsum redistribution is a necessary qualifier because the social planner ignores endowments and transfers in both the IEES (as evident from (22)) and the neoclassical economy. In both models lumpsum transfers to consumers are feasible. But one would also need to redistribute the organisms' endowments (20) to be able to decentralize each and every solution of (22). Yet, the redistribution of these endowments is not at the social planner's disposal because these endowments are meant to be intrinsic attributes of the organisms. This is why the second theorem of welfare economics cannot be fully extended from models of the economy to the IEES.

The next proposition highlights the relation between economic and ecosystem prices.

Proposition 3.

(i) *In an efficient general equilibrium of the IEES*

- *the economic price of biomass of species i is*

$$p_{hi} = \pi_{zi} + \underbrace{\frac{p_{yg}}{H_{yig}^i}}_{[1]} = \pi_{zi} + \theta_{zi} \quad \text{all } i, \text{ any } g, \quad (23)$$

- *the economic price of land services is*

$$p_r = \pi_s - \underbrace{\sum_k \frac{p_{yg} U_{qck} Q_r^k}{U_{ycg}}}_{[2]} + \underbrace{\frac{p_{yg}}{R_{yrg}} \left[\delta - \left(\frac{p_{yg}}{R_{yrg}} \right) \frac{R_{yrg}}{p_{yg}} \right]}_{[3]} - \underbrace{\frac{p_{yg} R_r}{R_{yrg}}}_{[4]} \quad \text{any } g, \quad (24a)$$

$$p_r = \theta_r + \frac{p_{yg}}{R_{yrg}} \left[\delta - \left(\frac{p_{yg}}{R_{yrg}} \right) \frac{R_{yrg}}{p_{yg}} \right] - \frac{p_{yg} R_r}{R_{yrg}}. \quad (24b)$$

(ii) *In a steady state of the efficient general equilibrium of the IEES*

- *the price of (a living organism of) species i is*

$$\beta_i^* = \frac{1}{\delta} \left(\underbrace{\sum_k \frac{p_{yg}^* U_{qck} Q_{n_i}^k}{U_{ycg}}}_{[5]} - \underbrace{\pi_s^* \omega_i}_{[6]} + \underbrace{\frac{\varepsilon(h_i, n_i)(p_{hi}^* - \pi_{zi}^*) h_i}{n_i}}_{[7]} + \underbrace{\frac{\pi_{zi}^* h_i}{n_i}}_{[8]} \right) \quad \text{any } g, \quad (25)$$

where $\varepsilon(h_i, n_i) := n_i H_{n_i}^i / h_i > 0$;

- the price of (a unit of) economic land is

$$\rho^* = \frac{1}{\delta - R_r} \left(p_r^* - \frac{\pi_s^* R_r}{\delta} + \underbrace{\sum_k \frac{p_{yg}^* U_{qck} Q_r^k}{U_{ycg}}}_{[2]} \right) \quad \text{any } g, \quad (26)$$

- the price of (a unit of) habitat is

$$\gamma^* = \frac{\pi_s}{\delta}. \quad (27)$$

To capture the essence of (23) recall that 'harvesting' of prey biomass by predators in the ecosystem is costless whereas human predators incur positive marginal harvesting costs [1]. With zero marginal costs of harvesting, i.e. with $H_{yig}^i \rightarrow \infty$, (23) yields $p_{hi} = \pi_{zi}$. Hence efficiency requires the biomass price of all species i to be the same in both submodels for all species i that are harvested unless asymmetric conditions in both markets warrant a price difference. Although (24a) looks much more complex than (23), the same argument applies for the prices of land services in both subsystems. In [4] the stock externality $R_r < 0$ increases the marginal conversion costs, p_{yg}/R_{yrg} , that are positive in the economy but have no equivalent in the ecosystem. To rule out marginal conversion costs as a cause of divergence suppose that $R_{yrg} \rightarrow \infty$. This assumption eliminates [4] as well as the dynamic marginal costs [3]. The remaining factor [2] that renders different the efficient land prices in both submodels represents the external marginal costs generated by the ecosystem services externality which exists in the economy but has no counterpart in the ecosystem. In fact, if that externality is 'switched off' (for the sake of the argument) by setting $U_{qck} \equiv 0$, then (24a) is turned into $p_r = \pi_s$. In other words, efficiency requires land services to be uniformly priced in both subsystems unless these subsystems exhibit differences in internal and external marginal costs.

Dynamic marginal land conversion costs [3] accrue in the economy but not in the ecosystem because humans determine the size of habitat unilaterally and the land conversion firm controls for the time path of economic land use. The dynamic marginal costs comprise two components. $\frac{\delta p_{yg}}{R_{yg}}$ reflects that increasing land conversion diminishes the available land stock. $-\left(\frac{p_{yg}}{R_{yg}}\right)$ captures the costs of keeping land in stock. If $\left(\frac{p_{yg}}{R_{yg}}\right) > 0$, the market value of economic land increases and the land converting firm will keep the land in stock. If $\left(\frac{p_{yg}}{R_{yg}}\right) < 0$ the market value of the stock decreases and it may be expensive not to convert land in good time.

β_i^* from (25) is the price of a living organism i in the long-run equilibrium that is made up of the present value of the components [5] - [8]. The term [5] represents the external

benefits of the marginal organism i in form of enhancing the provision of public ecosystem services; [7] is the marginal benefit of the stock externality $H_{n_i}^i > 0$; [8] gives us the value of organism i 's biomass loss due to harvesting. The value β_i^* is reduced by the value of organism i 's land endowment [6] which represents the opportunity costs of economic land use.

In (26), ρ^* is the efficient steady state price of economic land. It equals the present value of the price of economic land services, $p_r^*/(\delta - R_r)$, (where the relevant discount rate is not δ but $(\delta - R_r) > \delta$) reduced by two corrective factors: the present value of the opportunity costs of the stock externality, if land were provided in the ecosystem, $\pi_s^* R_r/(\delta - R_r)$, and the present value of the term [2] that has already been described above. Finally, the price γ^* of the habitat is simply the present value of the ecosystem price for land.

Based on Proposition 3(ii) we are able to calculate the value of the ecosystem in an efficient steady state. The total value of all species is

$$\sum_i \beta_i^* n_i = \frac{1}{\delta} \left[\underbrace{\sum_i \sum_k \frac{p_{yg}^* U_{qck} Q_{n_i}^k}{U_{ycg} n_i}}_{[9]} - \underbrace{\pi_r^* s}_{[10]} + \underbrace{\sum_i \varepsilon(h_i, n_i)(p_{hi}^* - \pi_{zi}^*) h_i}_{[11]} + \underbrace{\sum_i \pi_{zi}^* h_i}_{[12]} \right]. \quad (28)$$

That value is composed of

- the species' contribution to the aggregate marginal benefits of public ecosystem services [9] minus
- the total value (at the ecosystem price of land services) of the habitat [10] plus
- the aggregate value of all stock externalities in harvesting [11] plus
- the total value (at ecosystem prices) of all biomass harvested by humans [12].

From (26) - (28) it is straightforward to compute the total value of the ecosystem in an efficient steady state as

$$\sum_i \beta_i^* n_i + \gamma^* s = \frac{1}{\delta} \left[\sum_i \sum_k \frac{p_{yg}^* U_{qck} Q_{n_i}^k}{U_{ycg} n_i} + \sum_i \varepsilon(h_i, n_i)(p_{hi}^* - \pi_{zi}^*) h_i + \sum_i \pi_{zi}^* h_i \right] \quad (29)$$

and the value of the entire stock of land as

$$\rho^* r + \gamma^* s = \frac{1}{\delta - R_r} \left(\underbrace{p_r^* r}_{[13]} + \pi_s^* s \left(1 - \frac{(s-r)R_r}{\delta s} \right) + \underbrace{\sum_k \frac{p_{yg}^* U_{qck} Q_r^k}{U_{ycg}} r}_{[14]} \right). \quad (30)$$

It is interesting to observe that the value of habitat [10] cancels out when deriving the value of the ecosystem (29). Suppressing stock externalities, formally $H_{n_i} = R_r \equiv 0$, the formulas (29) and (30) have straightforward and appealing interpretations. The value of the ecosystem then consists of the benefits from ecosystem services [9] and from the value of biomass harvested [12]. The value of the entire stock of land is then composed of the value of economic land services [13] plus the value of habitat [10] minus the external cost of economic land use [14].

5 Concluding remarks

The main purpose of the present paper is methodological and conceptual but it aims, at the same time, to demonstrate that the application of a general-equilibrium competitive allocation mechanism to a microfounded integrated ecological-economic system yields specific and new insight with regard to efficient pricing of the ecosystem and its services. The ecosystem and the economy are designed as interdependent submodels and the focus is on intra-system interactions of individuals as well as on inter-system repercussions of these interactions. Both submodels are characterized by resource scarcity and a decentralized and uncoordinated mode of allocating resources. The competitive mechanism therefore appears to be an appropriate methodological device to 'coordinate' the activities of optimizing agents through prices. For economists, the ultimate way of assessing scarcity and value is to put a price tag on the items under consideration. On the conceptual level we have shown that our approach generates such prices in both submodels, and that it is able to determine and compare the prices of goods, namely land services and biomass, that are traded in both subsystems on competitive but disconnected markets.

As in other studies, in our analysis the source of inefficiencies remains, of course, the "... interplay of properly defined property rights, externalities and market failure" (Brown 2000, p. 875). Yet our approach allows a fresh diagnosis. In *laissez-faire*, economic agents disregard the ecosystem prices of land and biomass (as they disregard other non-market spillovers) which calls for corrective regulation. We have shown that there are taxes on economic land use and taxes on harvested biomass that are capable to restore efficiency. Quantity (rather than price) regulation clearly is an alternative way toward allocative efficiency being applied in practice in form of harvesting quotas, land use restrictions, land zoning etc.

Although the paper does not focus on applied techniques of valuating ecosystem components, our approach has the potential to serve as a basis for a new kind of applied general

equilibrium analyses. By now, such analyses have become a standard tool for simulating the incidence of *economic* policies with significant ramifications in many *economic* markets. With appropriate parametrizations and calibrations of both the economic and the ecosystem submodel¹⁹ one would be able to run numerical simulations in a large-scale IEES to gauge the quantitative impact on the whole system of alternative policies of biomass harvesting and economic land use. Such applications would generate numerical information on ecosystem prices and values that would be an important input in designing efficient natural resource policies.

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¹⁹In different but related frameworks Finnoff and Tschirhart (2003a, 2003b) calibrate a fairly complex general equilibrium model of the ecosystem and study the repercussions of harvesting strategies in numerical analysis.

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Appendix

Proof of Proposition 1:

Proposition 1 follows from applying Theorem 11 in Seierstad and Sydsæter (1987, chapter 6, p. 385). We devoted to trace the requirements of that Theorem 11 in all detail. However, the main substantive conditions are listed in Proposition 1. ■

Proof of Proposition 2:

To prove Proposition 2 we substitute in the second column of Table 1 all equations listed in Proposition 2 which renders identical the equations in the lines 1 through 11 in both columns of Table 1. ■

Proof of Proposition 3:

Equations (23), (23) and (26) follow from the equations in lines 2 and 9 (column general equilibrium) of Table 1 taking into account θ_{hi} and θ_r from Proposition 2.

Equation (25) is proven as follows: From line 10 in Table 1:

$$\beta_i^* = \frac{1}{\delta} \left(\sum_k \frac{p_{yg}^* U_{qck} Q_{n_i}^k}{U_{y_{cg}}} + \frac{p_{yg}^* H_{n_i}^i}{H_{y_{ig}}^i} - \pi_r^* r_i - \sum_j \pi_{zj}^* z_{ij} \right).$$

Making use of the budget constraint defined in (19):

$$\beta_i^* = \frac{1}{\delta} \left(\sum_k \frac{p_{yg}^* U_{qck} Q_{n_i}^k}{U_{y_{cg}}} + \frac{p_{yg}^* H_{n_i}^i}{H_{y_{ig}}^i} - \pi_r^* \omega_i - \frac{\pi_{zi}^* h_i}{n_i} \right).$$

Invoking (23) we obtain

$$\frac{p_{yg}^* H_{n_i}^i}{H_{y_{ig}}^i} = (p_{hi}^* - \pi_{zi}^*) H_{n_i}^i = \frac{(p_{hi}^* - \pi_{zi}^*) h_i}{n_i} \cdot \frac{n_i H_{n_i}^i}{h_i}.$$

Equations (27) and (28) follow from the first order conditions

$$\begin{aligned} \dot{\rho} &= \rho\delta - \rho R_r + \gamma R_r - \alpha_r - \sum_k \alpha_{qk} Q_r^k, \\ \dot{\gamma} &= \gamma\delta - \alpha_s \end{aligned}$$

of (22). Setting $\dot{\rho} = \dot{\gamma} = 0$ and using the information of Proposition 2 yields the desired equations. ■