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ANALYSIS

Valuation of ecosystem goods and services Part 1: An integrated dynamic approach

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ABSTRACT

This is the first part of a two-part paper which offers a new approach to the valuation of ecosystem goods and services. The existing literature on environmental valuation is based on two distinct foundations. The *ecological valuation methods* derive values by a cost-of-production approach. Their common characteristic is the neglect of consumer preferences. The *economic valuation methods* focus on the exchange value of ecosystem services. Their common characteristic is that they are finally based on consumer preferences, and do not adequately take account of the complex internal structure of ecosystems.

As the existing methods for the valuation of ecosystem services emphasize either the economic system or the ecosystem, the main objective of part 1 is to provide the conceptual foundations for a new method of valuation of ecosystem services, which deals simultaneously with the ecosystem, the economic system and society in a balanced way. Within a simple pre-industrial model it is shown how the interdependencies between the three subsystems influence values, and how values change over time.

1. Introduction

The *valuation of ecosystem goods and services* is one of the main topics in ecological economics, as is shown by three special issues and some 180 articles published in this journal alone, covering different aspects of 'valuing nature'. As most of these contributions apply existing methods rather than questioning existing valuation paradigms, it seems to me that ecosystem valuation still lacks a coherent conceptual and methodological foundation. Nevertheless, the academic discussion is gaining 'structure' in the sense that most contributions are based on two different conceptual foundations: the common characteristic of the *ecological valuation methods* is their *neglect of human needs and wants*, while the common characteristic of the *economic valuation methods* is their emphasis on *consumer preferences*. In summary, the existing approaches either emphasize the ecosystem or the economy. For a valuation method, which can be used to guide human behavior towards an efficient and sustainable use of natural resources, a *balanced* approach is necessary.

This is the first part of a two-part paper, whose aim is to highlight the strengths and weaknesses of the existing approaches and to propose a new conceptual foundation for the valuation of ecosystem goods and services, which is based on the strong aspects of the two methodological foundations. Therefore, I shall argue for an *integrated* approach, which deals simultaneously with nature, economy and society.

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In the first part, I show that values depend on the complex interrelationship of these three subsystems. Moreover, most valuation approaches are static or quasi-static. Especially in the context of the valuation of ecosystem goods and services this is an unjustified oversimplification, as there are often trade-offs between the short-term and long-term use of nature. Thus, a suitable valuation method has to take into account irreversibility and long-term consequences. As a consequence, values are not *static* but *dynamic* and depend on the *co-evolution* (i.e. the mutually interdependent development) of the three subsystems nature, economy and society.

In the second part, the problem of ignorance about the future development of the system will be addressed. Within the long-term perspective needed in ecosystem valuation, the three subsystems nature, economy and society cannot be assumed to co-evolve in a known and predictable way. In fact, all three subsystems are subject to *novel* (i.e. in principle unpredictable) change. This limits humankind's possibility to derive accurate estimates of the values of ecosystem goods and services.

In the remainder of part 1, I first discuss in detail the strengths and weaknesses of the existing valuation methods (Section 2). Then, in Section 3, I introduce a simple pre-industrial model to illustrate

- that values are determined by the complex interdependencies of the three subsystems nature, economy and society (Section 4), and
- that values are in general dynamic and depend on the co-evolution of the three subsystems (Section 5).

Finally, the resulting consequences are addressed in Section 6.

2. Ecological versus economic valuation methods

First, I briefly discuss the two different conceptual foundations on which most contributions to ecosystem valuation rest. As I shall argue in the following, both of these approaches have strengths and weaknesses. Thus, I suggest the combination of the strengths of both approaches in order to achieve a new *integrated* and *dynamic* concept of value as presented in Section 3.

2.1. Ecological valuation methods

The common characteristic of the ecological valuation methods is their *neglect of human needs and wants*. Hence, humankind plays no particular role in the derivation of values. As a consequence, ecosystem goods and services in these approaches are all physical or nonphysical output produced by nature independently of their relationship to humankind. In particular, there are two different approaches to derive such *ecocentric* values.

The ecological valuation methods are either based on an *energy theory of value* or on an *economic–ecological analogy*. In the first case they are based on thermodynamic principles, where solar energy is considered to be the only primary input to the ecosystems (e.g. Odum, 1971, 1983; Odum and Odum, 2000; Slesser, 1973; Gilliland, 1975; Hannon, 1976, 1985; Hannon et al., 1986; Costanza, 1980; Cleveland et al., 1984 and Hall et al., 1992). The idea is similar to the classical *labor theory of value* as proposed by Ricardo ([1817]1953) and Sraffa (1960). One can derive the *exchange values* of all goods and services of the ecosystem in terms of the numeraire solar energy by a cost-of-production approach if solar energy (i) is the sole primary (i.e. nonproducible) factor of production and (ii) is an essential input to the production of all goods and services. Note that this is an accounting approach in the sense that value is reduced to the content of solar energy embodied in different products.

In the second case, the ecosystem is modelled analogously to an economic system within the framework of a generalized linear production model according to von Neumann (1945/46), Koopmans (1951) and Malinvaud (1953) (e.g. Amir, 1989, 1994; Klauer, 2000), or within a general equilibrium model following Arrow and Debreu (1954) and Debreu (1959) (e.g. Tschirhart, 2000; Pethig and Tschirhart, 2001; Finnoff and Tschirhart, 2003). They derive values based on the duality of quantities and shadow prices. Therefore, it has to be assumed that nature maximizes an objective function similar to the welfare maximization in economics. As nature is usually considered to be 'aimless', the concept of value is limited to the degree to which an item contributes to an objective or condition in a system, e.g. the stability of the system or the net mass output (Farber et al., 2002).

The strength of the ecological valuation methods is the explicit consideration of the internal structure of ecosystems. They emphasize the connectedness of different ecosystem entities by modelling the complex interrelationship between different parts of the whole ecosystem. However, they also face some difficulties. In the case of the energy theory of value approaches, solar energy can only be supposed to be the unique scarce factor in production on a global and long-term scale (Patterson, 1998). Moreover, the energy theory of value is not a suitable concept to answer the question of how we should spend our scarce resources on the co-evolution of humankind and nature. First, quite differently from the classical labor theory of value, the total available amount of solar energy is not at our command. As a consequence, we cannot decide which commodities we want to exchange with each other according to their energy equivalent exchange values.[1] Second, the energy theory of value neglects the value of different ecosystem services according to their ability to maintain and sustain the system as a whole. The main shortcoming of the ecology–economy analogy approaches is that the derived values give no insight into how the corresponding ecosystem products contribute to human well-being or long-run survival. In addition, it is difficult to justify, on theoretical grounds, an objective function which nature is supposed to maximize (Patterson, 2002).

[1] However, if it turns out that energy prices and market prices are strongly correlated as some contributions claim (e.g. Costanza, 1980; Costanza and Herendeen, 1984; Cleveland et al., 1984; Kaufmann, 1992), they can contribute to an integrated ecological and economic national (and global) accounting. This would form an indicator for weak sustainability, which might contribute to environmental policy.

2.2. Economic valuation methods

The common characteristic among the economic valuation methods is their emphasis on consumer preferences. According to the principle of *methodological individualism*, only human individuals determine values and reveal them by making decisions. As a consequence, ecosystem goods and services are all natural products which influence human well-being directly or indirectly. Moreover, their value is their contribution to user-specific goals, objectives or conditions (Costanza, 2000). All economic valuation methods focus on the exchange value of ecosystem services, which is the trading ratio of these goods and services. If they were to be traded on markets, the exchange value would simply be their market price. As many of the ecosystem services have public good properties, there is no simple way to introduce markets for these services.

Several economic valuation methods, such as contingent valuation, hedonic pricing and cost–benefit analysis, have been established to derive the exchange values when market valuations do not capture adequately the social value (e.g. O'Connor and Spash, 1999; Garrod and Willis, 1999; Heal, 2000a; Farber et al., 2002) and have been applied to the valuation of ecosystem services and natural capital on a regional (e.g. Daily and Ellison, 1999), national (e.g. Navrud and Pruckner, 1997; El Serafy, 1997) and global scale (e.g. Costanza et al., 1997; Boumans et al., 2002).

The strength of the economic valuation methods is that their concept of value incorporates the relationship between humankind and ecosystem products. However, the economic valuation methods also face severe difficulties. Often they do not adequately take account of the internal structure of ecosystems. Hence, they neglect the ecological interdependencies of different ecosystem entities. Furthermore, by relying on revealed or stated preferences, the economic valuation methods are not able to capture *normative and ethical aspects* of ecosystem valuation.

2.3. Synthesis

In summary, the existing approaches either emphasize the ecosystem or the economy. Following Costanza (2000) and Farber et al. (2002) in defining 'value' as the contribution of an action or object to user-specific goals, objectives or conditions, the valuation of ecosystem goods and services has no virtue in itself. In fact, it merely is a tool to guide human actions towards an efficient and sustainable use of natural resources. Therefore, an *integrated* approach is needed, which deals simultaneously with nature, economy and society. I shall argue that values depend on the complex interrelationship of these three subsystems. Moreover, most valuation approaches are static or quasi-static. Especially in the context of the valuation of ecosystem goods and services, this is an unjustified oversimplification, as there are often tradeoffs between the short-term and long-term use of nature. Thus, a suitable valuation method has to take into account irreversibility and long-term consequences. Therefore, values are not *static* but *dynamic* and depend on the *co-evolution* of the three subsystems nature, economy and society.

3. The model

In the following I sketch the conceptual foundation for an integrated dynamic approach for the valuation of ecosystem goods and services. The essential features of this new conceptual foundation are:

1. An integrated model of the three subsystems nature, economy and society and their mutual interdependencies.
2. Society is not, as in the economic valuation methods, represented by consumer preferences alone, but by a *value system*. Such a value system allows for the combination of both descriptive needs and wants, and normative ethical considerations.
3. The dynamic change of the system and its implications for the valuation of ecosystem goods and services are explicitly taken into account.As a paradigm, I introduce a simple pre-industrial economy–ecology model in an optimal control theoretical framework. In this model, a fixed human population shares a piece of land with a native species of animals. Interaction with nature occurs by different activities available to humankind, such as hunting the animal species, converting wilderness into farmland and cultivating the farmland. Furthermore, humankind is endowed with a value system, which enables them to evaluate different intertemporal development paths. However, neither the simple economy–ecology model itself nor the methodological approach of optimal control theory is crucial, but solely serves to form a simple paradigm. Nevertheless, the example is constructive in the sense that it outlines how the dynamic aspect of values and the interconnectedness of the three subsystems can be addressed in a standard optimal control setting.

3.1. The model world

Consider a human tribe which discovers an isolated island of size 1 and decides to make it their new home. At time $t=0$ the island is completely covered by (homogeneous) wilderness w, which is the habitat of the native animal species bison b. For the sake of simplicity, I do not consider any growth of the human society. As a consequence, the human society commands the fixed amount λ of labor at any time t, which can be assigned to the following three activities:

1. convert wilderness into farmland f,
2. cultivate farmland to produce food and
3. hunt bison to produce food.

The conversion of wilderness into farmland, by the use of labor, is an *irreversible* process, which is governed by the following differential equation

$$\dot{f}(t) = \alpha_1 l_1(t), \qquad \alpha_1>0, \tag{1}$$

where l_1 denotes the amount of labor assigned to the conversion of wilderness into farmland. For simplicity of presentation, the conversion of wilderness into farmland is considered to be a linear process with constant returns to scale, i.e. the amount of labor needed to convert an additional unit of wilderness equals $1/\alpha_1$, no matter what is the level of farmland which has already been converted from wilderness. At any time t, the remaining amount of wilderness equals the total size 1 of the island minus farmland:

$$w(t) = 1 - f(t). \tag{2}$$

Farmland can be cultivated to produce food according to the following Cobb–Douglas production function with constant returns to scale

$$P(f(t), l_2(t)) = [\alpha_2 f(t)]^{\delta}[\alpha_3 l_2(t)]^{1-\delta}, \qquad \alpha_2, \alpha_3 > 0, \qquad 0 < \delta < 1, \tag{3}$$

where l_2 is the amount of labor assigned to the cultivation of farmland, α_2 and α_3 are scaling factors measuring the productivity of farmland and labor, and δ and $1-\delta$ are the production elasticities of farmland and labor. In the remainder of part 1 I assume that α_2 and α_3 are equal to one and, thus, simply drop out of Eq. (3). This assumption will be dropped in part 2 of the paper, where I shall discuss the implications of novel change on the valuation of ecosystem goods and services.

In addition, food can be produced by hunting bison

$$H(b(t), l_3(t)) = \alpha_4 b(t) l_3(t), \qquad \alpha_4 > 0, \tag{4}$$

where l_3 is the amount of labor assigned to hunting and α_4 is a scaling factor for the productivity of hunting. The success of hunting is positively correlated with the level of the bison population. This amounts to the assumption that the more abundant are the bison on the island, the less effort is needed to hunt a certain amount of bison. Nevertheless, for every time t, and thus for any level of the bison population b, hunting is considered to be a linear process with constant returns to labor. This amounts to the assumption that the bison population is only marginally affected by hunting at any moment in time. Overall consumption c is farmland production P plus the outcome of hunting H:

$$c(t) = P(f(t), l_2(t)) + H(b(t), l_3(t)) = f(t)^{\delta} l_2(t)^{1-\delta} + \alpha_4 b(t) l_3(t). \tag{5}$$

The bison population lives in the wilderness, develops according to a logistic growth function, and is reduced by hunting

$$\dot{b}(t) = \beta b(t)\left[1 - \frac{(1-\theta)b(t)}{w(t)-\theta}\right] - \alpha_4 b(t) l_3(t), \qquad \beta > 0, \tag{6}$$

where β measures the reproductive capabilities of bison. The equilibrium level of the bison population crucially depends on the level of wilderness remaining. Without hunting, the equilibrium level of the bison population is 1 if $w = 1$, and it is 0 if $w \leq \theta$. In fact, the bison population is eradicated once wilderness reaches the threshold θ. Furthermore, wilderness is supposed to deliver irreplaceable life support functions for humans. For the sake of simplicity, I assume that the provision of these is not negatively affected at all as long as the level of wilderness does not fall below the threshold θ. Hence, in the model θ serves two purposes: (i) it is the minimal level of wilderness needed to ensure unconstrained life support services for humankind, and (ii) is also the crucial level of habitat size where the bison population becomes extinct. The double use of θ is not crucial but simplifies the analysis. However, the important point is that a certain level of 'natural capital' is enough to provide vital life support services for humankind, but at the same time it is not enough for the survival of some other species.

Thus, like the ecological valuation approaches, the model world comprises a simple ecosystem, consisting of wilderness and bison and the interdependencies between them. But in addition, the model also incorporates a simple economy, where humankind can assign labor to different kinds of productive activity, and takes into account the interdependencies and repercussions between the ecosystem and the economic system.

3.2. *Society's value system*

Suppose the human society agrees on a value system, i.e. the constellation of norms and precepts that guide humans in assigning importance and necessity, and also imply practical objectives and actions (Farber et al., 2002). This value system allows society to consider different development paths of the (model) world as more or less favorable. It is comparable to the concept of revealed or stated preferences in the economic valuation methods. But different from these, where preferences are derived ex post from individual actions, the value system has to be agreed ex ante to guide further actions. In addition, it may change over time (this will be discussed in part 2).

Indeed, this is a normative approach in the sense that society has to agree on how it wants to assign weights to different activities, and which restrictions it wants to impose on its future behavior. Hence, the value system is not just a descriptive approach to reflect human wants and needs, but it also allows for normative and ethical considerations. Moreover, such a concept of value is not necessarily *anthropocentric*, depending on the normative and ethical considerations incorporated for the right of nature to exist. Nevertheless, as it is the *human* society which agrees on it, it is clearly *anthropogenic*.

Admittedly, the existence of an ex ante agreed value system is a strong assumption. In general the agreement on such a value system is a *political process*. Depending on the scale of the total system boundaries, a local, regional, national or international agreement has to be found. Recent experiences in the negotiation (and the subsequent ratification) of international agreements, such as the Kyoto Protocol (United Nations Third Conference of the Parties of the Framework Convention on Climate Change, 1997) or the Cartagena Protocol on Biosafety (Secretariat of the Convention on Biological Diversity, 2000), have shown the political problems in achieving global agreements. However, the problems related to achieve a societal agreement are themselves a dynamic field of economic and political research and beyond the scope of this paper.[2]

In order to incorporate both descriptive aspects of human needs and wants, and normative ethical considerations, the

[2] In fact, positive political theory splits in two main research areas. The first is the axiomatic theory of individual preference aggregation. Early contributions from Arrow (1951) and Harsanyi (1955) have been refined for example by Campbell and Kelly (2000), and Mori (2003). The second is the game theoretic approach to analyze coalition formation and strategic voting behavior (e.g. Grossman and Helpman, 1996; Jackson and Moselle, 2002, Riker, 1962).

value system comprises two parts. The first part is a functional relationship, which measures trade-offs and substitution relationships between different aspects of the model world with their respect to either the well-being of humankind or normative ethical considerations. The second part is a set of restrictions, to capture minimum requirements, which cannot be substituted by other aspects (e.g. minimum amount of natural capital to guarantee the long-run survival of humankind), or ethical considerations, which are non-negotiable (e.g. human rights, existence rights for nature).

As an example of a value system, I assume that society seeks to find the set and timing of possible actions which maximize the following intertemporal functional W, which depends on human consumption c and the amount of remaining wilderness w:

$$W = \int_0^\infty V(c(t), w(t)) \exp[-\rho t] dt. \tag{7}$$

Here V represents a twice continuously differentiable and concave function and ρ is a positive and constant discount rate. For the sake of simplicity, consider V to be the following additively separable function:

$$V(c(t), w(t)) = \gamma \ln[c(t)] + (1-\gamma) \ln[w(t)], \qquad 0<\gamma\leq 1, \tag{8}$$

where γ weighs the relative importance of consumption to the objective functional W. Hence, society considers a substitution relationship between consumption and wilderness with the relative weights γ and $1-\gamma$.

Moreover, society's value system incorporates the following restriction:

$$w(t) \geq \theta, \quad t \in [0, \infty). \tag{9}$$

As θ is the minimal level of wilderness for which unconstrained provision of vital life support systems for humankind is guaranteed, this restriction ensures that society does not compromise on the natural foundations of its long-run survival. In general, society may agree on an additional set of restrictions, such as a minimal amount of bison.

In order to find feasible paths for l_1, l_2 and l_3, which maximize Eq. (7) and do not contradict Eq. (9), society solves the following optimal control problem:

$$\max_{l_1, l_2, l_3} \int_0^\infty V(c, w, \gamma) \exp[-\rho t] dt, \tag{10a}$$

subject to

$$c(t) = f(t)^\delta l_2(t)^{1\delta} + \alpha_4 b(t) l_3(t), \quad \text{(consumption possibilities)} \tag{10b}$$

$$\lambda = l_1(t) + l_2(t) + l_3(t), \qquad \text{(labor use)} \tag{10c}$$

$$\dot{f}(t) = \alpha_1 l_1(t), \qquad \text{(farmland conversion)} \tag{10d}$$

$$\dot{w}(t) = -\alpha_1 l_1(t), \qquad \text{(wilderness loss)} \tag{10e}$$

$$\dot{b}(t) = \beta b(t) \left[1 - \frac{(1-\theta) b(t)}{w(t)-\theta}\right] - \alpha_4 b(t) l_3(t), \quad \text{(bison dynamics)} \tag{10f}$$

$$w(t) \geq \theta, \qquad \text{(minimal level of wilderness)} \tag{10g}$$

$$l_i(t) \geq 0, \qquad i = 1, 2, 3, \qquad \text{(non-negative labor use)} \tag{10h}$$

$$f(0) = 0, \quad w(0) = 1, \quad b(0) = 1. \qquad \text{(initial conditions)} \tag{10i}$$

Thus, like the economic valuation approaches, the model defines a relationship between the well-being of humankind and ecosystem goods and services. But in contrast to ex post derived preferences, the ex ante agreed value system is flexible enough to incorporate also normative and ethical considerations.

In summary, the simple pre-industrial economy–ecology model comprises of the three different subsystems nature (represented by wilderness and bison), economy (represented by the three activities and the production functions P and H) and society (represented by the value system and the maximization procedure), and their interdependencies (represented by the equations of motion for wilderness, bison and farmland). Moreover, the model incorporates important aspects of economy–ecology interactions, such as irreversibility, species extinction and minimum standards of nature necessary for the provision of life support functions for humankind.

4. Shadow prices and values

As is the case for the ecological valuation methods which are based on an ecosystem–economy analogy (Section 2.1), values in this model are based on the duality of quantities and shadow prices. Therefore, I analyze the *dual* problem of Eq. (10), which is to maximize the current-value Hamiltonian $\mathcal{H}$:

$$\begin{aligned} \mathcal{H} = {} & V(c, w, \gamma) + p_c(t)[f(t)^\delta l_2(t)^{1-\delta} + \alpha_4 b(t) l_3(t) - c(t)] \\ & + p_l(t)[\lambda - l_1(t) - l_2(t) - l_3(t)] + p_f(t)[\alpha_1 l_1(t)] - p_w(t)[\alpha_1 l_1(t)] \\ & + p_b(t)\left[\beta b(t)\left(1 - \frac{(1-\theta) b(t)}{w(t)-\theta}\right) - \alpha_4 b(t) l_3(t)\right] + p_\theta(t)[w(t)-\theta] \\ & + p_{l_1}(t) l_1(t) + p_{l_2}(t) l_2(t) + p_{l_3}(t) l_3(t). \end{aligned} \tag{11}$$

The variables p_c, p_l, p_w, p_b, p_θ, p_{l_1}, p_{l_2} and p_{l_3} are the so called *shadow prices* of the corresponding variables consumption c, labor l, wilderness w, bison b, and the restrictions (10g) and (10h). The shadow prices corresponding to the inequality restrictions (10g) and (10h) have positive values only if these restrictions are binding, otherwise they are zero. Along the optimal path the shadow prices indicate how much the functional (7) would increase, if the corresponding variable or restriction would be increased by a marginal unit. Thus, the shadow prices can be interpreted as the *values* of the corresponding entities. This is a concept of *relative values*, i.e. the values depend on the state and the development of the system.[3]

This interpretation of *values* has three immediate consequences. First, values (i.e. the shadow prices or dual variables) and activities (i.e. the control variables or primal variables) are inseparably interconnected, i.e. for every set of shadow prices there is a one to one mapping to a corresponding set of activities. Second, the values (and thus, also the activities) crucially depend on the underlying value system (7) and (9). In general,

[3] However, it is not a *marginal* concept of value in the sense that the shadow prices only reflect *present* demand and supply conditions (e.g. Heal, 2000b). In fact, due to the intertemporal framework applied, present shadow prices also take account of *future* demand and supply conditions, as can be seen in Eqs. (12b)–(12d).

a change of the value system implies a change of the shadow prices (and the activities). Third, the shadow prices are functions of time as the human–nature interactions evolve with wilderness loss and bison hunting. Hence, in general values change over time as the system develops, even if the value system and the production possibilities remain constant.

From the necessary and sufficient conditions derived in Appendix A.1 one obtains the following formulae for the shadow prices for consumption c, farmland f, wilderness w and bison b:

$$p_c(t) = \frac{\gamma}{c(t)}, \tag{12a}$$

$$p_f(t) = \int_t^\infty p_c(t')\delta f(t')^{\delta-1} l_2(t')^{1-\delta} \exp[-\rho(t'-t)]dt', \tag{12b}$$

$$p_b(t) = \int_t^\infty p_c(t')\alpha_4 l_3(t') \times \exp\left[-(\rho-\beta)(t'-t) - \int_t^{t'} \alpha_4 l_3(t'') + \frac{2\beta(1-\theta)b(t'')}{w(t'')\theta} dt''\right] dt', \tag{12c}$$

$$p_w(t) = \int_t^\infty \left(\frac{1-\gamma}{w(t')} + p_b(t')\frac{\beta(1-\theta)b(t')^2}{(w(t')-\theta)^2} + p_\theta(t')\right) \times \exp[-\rho(t'-t)]dt'. \tag{12d}$$

The Eq. (12a) states that along the optimal path, the shadow price of consumption p_c equals the marginal contribution of consumption to the value function V. According to Eq. (12b), the shadow price of farmland p_f is the discounted sum of all future contributions to the value function of an additional marginal unit of farmland expressed by the marginal productivity of farmland. As society values bison only indirectly as a potential provider of food, its shadow price p_b is positive only as long as a positive amount of labor is assigned to hunting. Again the shadow price equals the discounted sum of all future contributions to the value function of an additional marginal unit of bison, expressed by the marginal productivity of hunting. Unlike farmland and wilderness, bison reproduce. As a consequence the effective discount rate does not equal ρ but the term in the exponential function in Eq. (12c). Also the shadow price of wilderness p_w is the discounted sum of all future contributions to the value function of an additional marginal unit of wilderness. These future contributions are the compound of the direct value of wilderness as expressed in the value function, the indirect effect that wilderness allows for a higher bison population, which itself has a value as long as p_b is positive, and a contribution p_θ from the restriction (10g), if it is binding.

The situation is slightly more complicated for the shadow price of labor p_l. According to Eqs. (A.1a)–(A.1c) in Appendix A.1 one obtains three independent equations for p_l:

$$p_l(t) = [p_f(t) - p_w(t)]\alpha_1 + p_{l_1}(t) = 0, \tag{12e}$$

$$p_l(t) = p_c(t)(1-\delta)f(t)^\delta l_2(t)^{-\delta} + p_{l_2}(t) = 0, \tag{12f}$$

$$p_l(t) = [p_c(t) - p_b(t)]\alpha_4 b(t) + p_{l_3}(t) = 0. \tag{12g}$$

As p_l has the same value in all three equations (12e)–(12g), they determine to what extent society assigns labor to the three different activities. If society assigns labor to all three activities, then according to Eq. (A.1i) $p_{l_i}=0$ $(i=1,2,3)$. Then p_l equals, at the same time, the marginal welfare gain of converting wilderness into farmland (Eq. (12e)), the marginal welfare gain of the cultivation of farmland, and the marginal welfare gain of hunting. If the marginal welfare gain of activity i $(i=1,2,3)$ does not equal p_l, then $p_{l_i}>0$ and thus, no labor is assigned to the corresponding activity as the use of labor in the other activities produces a higher welfare gain. From Eqs. (12a)–(12g) it is clear that all shadow prices are non-negative.

5. Dynamic aspects of values

In the following section I discuss the dynamic aspect of values in more detail. As already noted in the previous section, the concept of value in this model is relative, i.e. values depend on the state of the system. In general, the state of the system changes over time, although the model equations and the exogenously given parameters stay constant over time. Nevertheless, the model exhibits the possibility of a *stationary state*, i.e. a state where the system stays constant over time. In such a stationary state also the (current) values do not change over time but remain constant.

5.1. *Long-run stationary state*

Due to the limited possibilities of development, the island society will eventually converge to a stationary state, where all dependent variables and the corresponding (current-value) shadow prices remain constant over time. For the sake of simplicity, I suppose that hunting is less productive than converting wilderness and cultivating farmland, and thus, society will hunt only as long as it takes to get enough wilderness converted into farmland.[4] Also cultivating will take place only until either wilderness reaches the threshold θ or until the welfare gain of converting an additional unit of wilderness does not outweigh the welfare loss in reducing wilderness. In the former case restriction (10g) is binding, while it is not in the latter. As a consequence, in the following I shall refer to the former case as the *corner solution* and to the latter as the *interior solution*. In either case, all labor will be assigned to the cultivation of farmland in the long run. Table 1 shows the dependent variables and the corresponding shadow prices in the long-run stationary state for the corner and the interior solution as derived in Appendix A.2.

Whether society achieves the corner solution or the interior solution in the long-run stationary state is not directly linked to society's explicit valuation of wilderness. On the one hand, an explicit valuation of wilderness (i.e. the relative weight for consumption $\gamma<1$) does not necessarily rule out the corner solution long-run stationary state, as society's valuation of wilderness might be too small to prevent wilderness to be diminished to the threshold θ. On the other hand, not explicitly valuing wilderness (i.e. the relative

[4] However, in general the model allows for long–run stationary states, where positive labor is assigned to both the cultivation of farmland and the hunting of bison.

Table 1 – Dependent variables and corresponding shadow prices in the long-run stationary state in the case of a corner solution and an interior solution

	Corner solution	Interior solution
$l_1^\star$	0	0
$l_2^\star$	λ	λ
$l_3^\star$	0	0
$c^\star$	$(1-\theta)^\delta\lambda^{1-\delta}$	$(1-w^\star)^\delta\lambda^{1-\delta}$
$f^\star$	$1-\theta$	$1-w^\star$
$w^\star$	θ	$w^{\star\,a}>\theta$
$b^\star$	0	$(w^\star-\theta)/(1-\theta)$
$p_l^\star$	$\gamma(1-\delta)/\lambda$	$\gamma(1-\delta)/\lambda$
$p_c^\star$	$\gamma/((1-\theta)^\delta\lambda^{1-\delta})$	$\gamma/((1-w^\star)^\delta\lambda^{1-\delta})$
$p_f^\star$	$\gamma\delta/(\rho(1-\theta))$	$\gamma\delta/(\rho(1-w^\star))$
$p_w^\star$	$\gamma\delta/(\rho(1-\theta))-\gamma(1-\delta)/(\alpha_1\lambda)$	$(1-\gamma)/(\rho w^\star)$
$p_b^\star$	0	0
$p_\theta^\star$	$\gamma\delta/(1-\theta)-\gamma(1-\delta)\rho/(\alpha_1\lambda)-(1-\gamma)/\theta$	0

[a] $w^\star=-\left([B+C-A]-\sqrt{[B+C-A]^2+4AC}\right)/2A$, with $A=\gamma\rho(1-\delta)$, $B=\gamma\lambda\alpha_1\delta$, $C=\lambda(1-\gamma)\alpha_1$.

weight for consumption $\gamma=1$) does not necessarily lead to the corner solution long-run stationary state. If the amount of labor needed to convert wilderness into farmland $1/\alpha_1$ is too high, or the production elasticity of farmland δ is too low, then wilderness will not be diminished to the threshold θ, despite society's neglect for valuing wilderness. However, society does not value bison explicitly but only as a provider of food as long as it hunts, and thus, in the long-run the shadow price of bison $p_b^\star=0$. As a consequence, bison become extinct in the corner solution but not in the interior solution.

The shadow price $p_\theta^\star$ is positive only if the restriction (10g) is binding, i.e. it is positive in the corner solution and zero in the interior solution. This shadow price measures, in terms of lost welfare, the cost imposed on society for obeying the restriction (10g). As I supposed that obeying restriction (10g) ensures unconstrained provision of vital life support systems for humankind, $p_\theta^\star$ can be interpreted as the societal cost for not compromising on the natural foundations of humankind's long-run survival.

5.2. *Evolution of values*

Although the system will eventually converge towards a stationary state, where all shadow prices are constant over time, there will be a transition phase from the initial state to the long-run stationary state, with the shadow prices changing over time. In this section this transition phase is analyzed in detail. Although the optimal control problem (10) is not analytically soluble, the evolution of the system and, thus, the evolution of values can be solved numerically for any given set of exogenous parameters. Fig. 1 shows numerical optimizations for two different scenarios for a fixed set of exogenous parameters. The details of the numerical optimization are given in Appendix A.3.

5.2.1. *Scenario 1: no explicit valuation of wilderness*

In the first scenario $\gamma=1$, i.e. the society does not explicitly value wilderness but solely consumption (left side of Fig. 1). Finally, the system converges to the corner solution long-run stationary state. The system's development splits into three different phases.

In the first phase, there is only little farmland. As a consequence, the society relies on hunting as the main source of consumption and, thus, labor is assigned to all three production processes. In the second phase, enough farmland for cultivation is available. As the cultivation of farmland is more productive than hunting, labor is only assigned to the conversion of wilderness into farmland and the cultivation of farmland. In the third phase, wilderness has been diminished to the threshold θ in favor of farmland, which then equals $1-\theta$. Hence, the long-run stationary state is reached and all labor is used solely to cultivate the farmland. During the first phase, the bison population drops significantly due to the combined effect of hunting and the loss of habitat. By the end of the second phase the bison population drops until it finally becomes extinct as wilderness reaches the critical threshold θ.

The shadow prices p_f, p_w and p_b are given in units of the shadow price of labor p_l (which itself is not constant over time but declining). This facilitates the comparison of the shadow prices derived from different sets of exogenous parameters. The shadow price of farmland p_f is increasing over time, because the marginal productivity of farmland is declining more slowly than the marginal productivity of labor. As a consequence, farmland is becoming relatively scarcer over time. In the long-run stationary state, the shadow price of farmland is constant and equals $p_f^\star$. As we already know from Eq. (12c), the shadow price of bison p_b is positive only as long as society hunts bison. As can be seen in Fig. 1, p_b declines rapidly during the first phase to remain at zero thereafter.

If society does not value wilderness explicitly, the shadow price of wilderness p_w reflects that wilderness is valued as the habitat of bison as long as society hunts, and that wilderness has a scarcity value due to the binding restriction (10g). During the first phase, p_w declines as the former part declines more rapidly than the latter increases. In the second phase, p_w is increasing to finally reach the shadow price $p_\theta^\star$ in the long-run stationary state, as the first part is constant zero and the second part is increasing. The difference between p_f and p_w equals p_l/α_1 at all times. Thus, as society does not value wilderness in its own, the shadow price of wilderness is the shadow price of farmland minus the costs it takes to turn it into

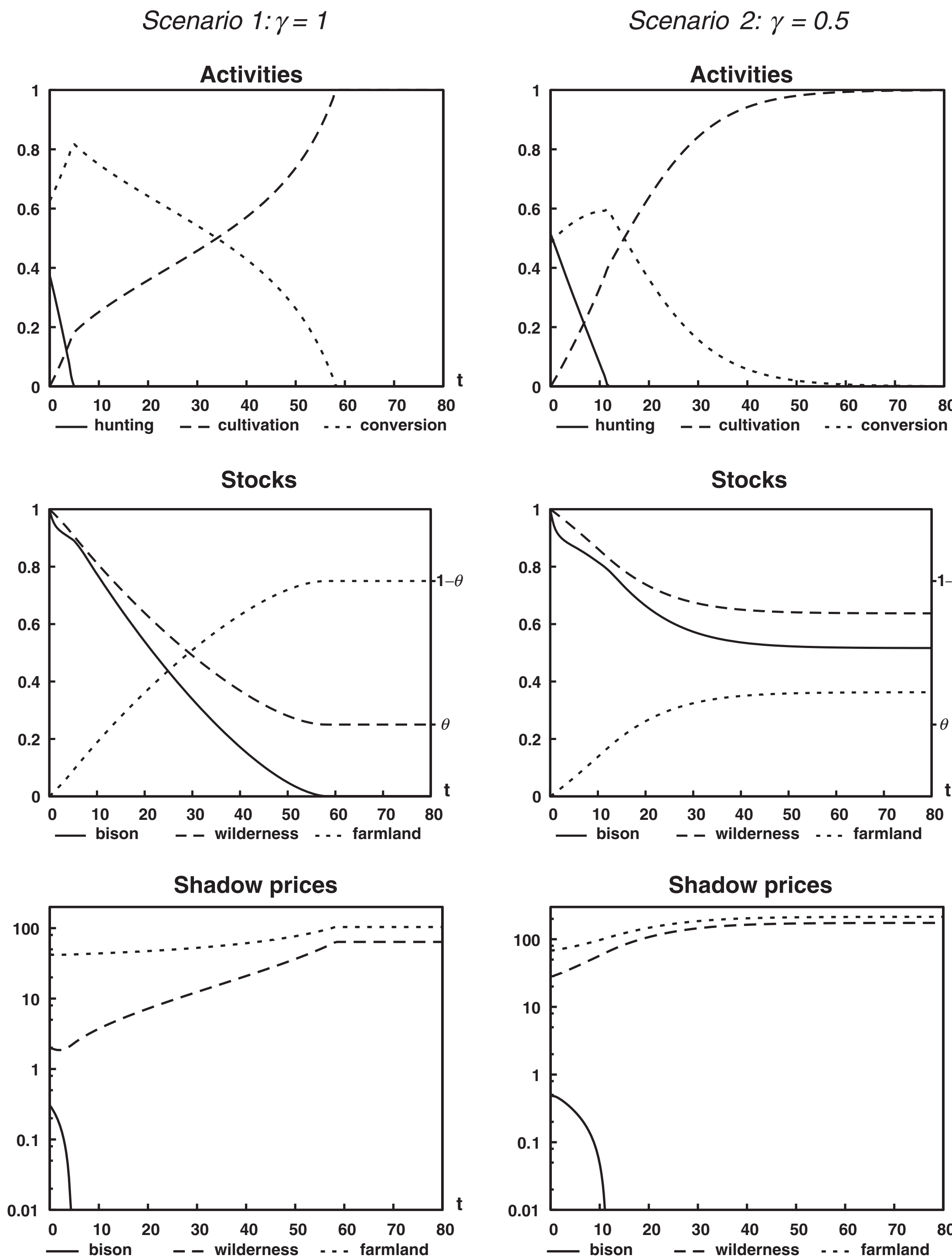

Fig. 1 – Optimal paths for activities (top), stocks (middle) and corresponding shadow prices (bottom) for $\gamma=1$ (left) and $\gamma=0.5$ (right). Details about the exogenous parameters are given in Appendix A.3.

farmland. As the shadow price of labor is declining over time, the gap between p_f and p_w is closing.

5.2.2. *Scenario 2: positive explicit valuation of wilderness*

In the second scenario $\gamma=0.5$, i.e. society values consumption and wilderness equally (right side of Fig. 1). In this case, the long-run stationary state is an interior solution. Again, the system's development splits into three phases, where labor is assigned to all three processes during the first phase, no labor is assigned to hunting during the second phase, and labor is assigned solely to cultivation in the third phase.

Again, the long-run stationary state is reached with the beginning of the third phase. Compared to the first scenario, society assigns more labor to hunting over a longer time span, as less wilderness is converted into farmland. As a consequence, the bison population declines strongly during the first phase, keeps declining during the second phase as habitat size decreases but remains at about half the size of the original population in the long-run stationary state. As in the first scenario, wilderness is converted into farmland but at a significantly slower pace. As a consequence, two third of the original wilderness remains in the long-run stationary state.

Analogously to the first scenario, the shadow price of bison p_b is positive only as long as society hunts. Again, the shadow price of farmland p_f is increasing over time, as farmland is becoming relatively more scarce. If wilderness is valued explicitly (i.e. $\gamma<1$) and the long-run stationary state is an interior solution, the shadow price of wilderness p_w reflects the value of wilderness as the habitat of bison as long as society hunts, plus the explicit existence value of wilderness, which is indirectly proportional to the amount of remaining wilderness. As the second contribution outweighs the first, the shadow price of wilderness p_w is monotonically increasing over time.

These two numerical examples illustrate the two main features of shadow prices or values. First, the optimal development of the system under consideration depends crucially on the value system. The optimal trajectories for the distribution of the available labor and, thus, the development of the system and the corresponding shadow prices differ between the two examples. This has some dramatic consequences for the bison population, which becomes extinct in the first scenario, but survives in the second scenario because society values wilderness strongly enough. Second, values are not constant over time but in general develop together with the system under consideration. Moreover, the development of the system is a *co-evolution* of all the three subsystems, as changes in one subsystem induce repercussions within the other two.

6. Conclusions

The valuation of ecosystem goods and services has no virtue in itself but is simply a tool to guide us, humankind, in how to treat and utilize nature in a way which complies to the maximal achievable extent with our interpretation of what Aristotle called the 'good life'. Although there is no unambiguous definition for the 'good life', it is clear that it has to incorporate both human needs and wants, and also normative and ethical considerations. Examples for the latter include existence rights for plant and animal species, sustainable development, and inter- and intragenerational justice. Once we have agreed on a definition of the 'good life', we then have to consider how our set of available actions directly or indirectly contributes to this goal. Therefore, we need to take into account the direct and indirect consequences that our actions impose on the ecosystem, the economic system and the society. As these three subsystems are intertwined, we also have to take into account the mutual interdependencies and repercussions between them. Thus, in order to derive accurate ecosystem values we have to adopt an integrated and dynamic view.

As the existing conceptual foundations of ecosystem valuation have in common that they neglect crucial parts of this integrated and dynamic system, there is a need for a new conceptual foundation, which combines the strengths of the existing approaches. To illustrate such an integrated dynamic approach, I introduced a simple pre-industrial economy–ecology model consisting of the three subsystems nature, economy and society, and their interdependencies. Moreover, the model incorporates such important aspects of economy–ecology interactions as irreversibility, species extinction and minimum standards of nature necessary for long-term human survival. Within this model, I have shown how the interdependencies between the three subsystems influence values and how values change over time due to the co-evolution of the three subsystems.

On the one hand the model presented serves as a paradigm to highlight the need of an encompassing approach in ecosystem valuation, which takes into account the interconnectedness of the three different subsystems and the dynamic aspect of values at the same time. On the other hand, the example is constructive in the sense that it shows how these problems can be addressed in a standard optimal control framework. Although it is unlikely that such a framework is tractable on a global scale, it is suitable for evaluation problems on a smaller scale. Examples include the management of fisheries and forests. In fact, Quaas et al. (2004), and Brock and Xepapadeas (2003) apply a similar framework to rangeland management and the valuation of biodiversity. In line with my approach they emphasize the intertemporal aspect and the interconnectedness between the economic system and the ecosystem.

In the model presented, the system converges towards a long-run stationary state, in which both the stocks and the corresponding shadow prices remain constant over time. In fact, often the assumption of a stationary state is utilized to neglect the dynamic issue of values. However, a long-run stationary state is a highly theoretical concept and, thus, a questionable assumption. This holds in particular in the case of long time horizons, which are usually necessary in ecosystem valuation due to trade-offs between short-term and long-term use of ecosystem goods and services. In fact, not only the stocks, activities and shadow prices change over time, according to the equations and the exogenous parameters of the model, but the model itself is subject to change. In general, all three subsystems experience novel change over time: ecosystems change due to genetic mutation, the political process influences and alters the value system, and inventions alter production possibilities. Moreover, these novel changes are in principal *unpredictable*. Obviously, this limits our possibility to determine accurate estimates for the values of ecosystem goods and services. This problem will be discussed in part 2.

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Appendix A

A.1. *Necessary and sufficient conditions*

The necessary conditions for an optimal solution of the optimal control problem (10) are:

$$\frac{\partial\mathcal{H}}{\partial l_1(t)}=-p_l(t)+\alpha_1 p_f(t)-\alpha_1 p_w(t)+p_{l_1}(t)=0, \tag{A.1a}$$

$$\frac{\partial\mathcal{H}}{\partial l_2(t)}=-p_l(t)+p_c(t)(1-\delta)f(t)^{\delta}l_2(t)^{-\delta}+p_{l_2}(t)=0, \tag{A.1b}$$

$$\frac{\partial\mathcal{H}}{\partial l_3(t)}=-p_l(t)+[p_c(t)-p_b(t)]\alpha_4 b(t)+p_{l_3}(t)=0, \tag{A.1c}$$

$$\frac{\partial\mathcal{H}}{\partial c(t)}=\frac{\gamma}{c(t)}-p_c(t)=0, \tag{A.1d}$$

$$\frac{\partial\mathcal{H}}{\partial f(t)}=-\dot{p}_f(t)+\rho p_f(t)=p_c(t)\delta f(t)^{\delta-1}l_2(t)^{1-\delta}, \tag{A.1e}$$

$$\frac{\partial\mathcal{H}}{\partial w(t)}=-\dot{p}_w(t)+\rho p_w(t)=\frac{1-\gamma}{w(t)}+p_b(t)\frac{\beta(1-\theta)b(t)^2}{(w(t)-\theta)^2}+p_\theta(t), \tag{A.1f}$$

$$\frac{\partial\mathcal{H}}{\partial b(t)}=-\dot{p}_b(t)+\rho p_b(t)=p_b(t)\left[\beta-\alpha_4 l_3(t)-\frac{2(1-\theta)b(t)}{w(t)-\theta}\right]+p_c(t)\alpha_4 l_3(t), \tag{A.1g}$$

$$p_\theta(t)\geq 0,\quad p_\theta(t)[w(t)-\theta]=0, \tag{A.1h}$$

$$p_{l_i}(t)\geq 0,\quad p_{l_i}(t)l_i(t)=0,\qquad i=1,2,3. \tag{A.1i}$$

Due to the concavity of the Hamiltonian $\mathcal{H}$, these necessary conditions are also sufficient, if in addition the following transversality conditions hold:

$$\lim_{t\to\infty} p_f(t)\exp[-\rho t]f(t)=0, \tag{A.2a}$$

$$\lim_{t\to\infty} p_w(t)\exp[-\rho t]w(t)=0, \tag{A.2b}$$

$$\lim_{t\to\infty} p_b(t)\exp[-\rho t]b(t)=0. \tag{A.2c}$$

Eqs. (A.1e)–(A.1g) are first order linear differential equations for the shadow prices p_f, p_w and p_b, which can be unambiguously solved together with the transversality conditions (A.2a)–(A.2c):

$$p_f(t)=\int_t^\infty p_c(t')\delta f(t')^{\delta-1}l_2(t')^{1-\delta}\exp[-\rho(t'-t)]dt', \tag{A.3}$$

$$p_b(t)=\int_t^\infty p_c(t')\alpha_4 l_3(t')\times\exp\left[-(\rho-\beta)(t'-t)-\int_t^{t'}\alpha_4 l_3(t'')+\frac{2\beta(1-\theta)b(t'')}{w(t'')-\theta}dt''\right]dt', \tag{A.4}$$

$$p_w(t)=\int_t^\infty\left(\frac{1-\gamma}{w(t')}+p_b(t')\frac{\beta(1-\theta)b(t')^2}{(w(t')-\theta)^2}+p_\theta(t')\right)\times\exp[-\rho(t'-t)]dt'. \tag{A.5}$$

A.2. *Long-run equilibrium*

The long-run equilibrium ($l_1^\star$, $l_2^\star$, $l_3^\star$, $f^\star$, $w^\star$, $b^\star$) is reached, if $\dot{f}(t)=\dot{w}(t)=\dot{b}(t)=0$. According to the equation of motion (10d) this implies that $l_1^\star=0$. If we further assume that hunting is less productive than the cultivation of farmland and thus hunting is only optimal until enough wilderness is converted into farmland, then also $l_3^\star=0$. As a consequence $l_2^\star=\lambda$. Furthermore, as $l_3^\star=0$ it follows from Eq. (A.1g) that $p_b^\star=0$.

A.2.1. *Corner solution*

In case of the corner solution, the restriction (10g) is binding and thus $w^\star=\theta$, $f^\star=1-\theta$ and $b^\star=0$. Inserting in Eq. (10b) yields $c^\star=(1-\theta)^\delta\lambda^{1-\delta}$. From Eq. (A.1d) follows:

$$p_c^\star=\frac{\gamma}{c^\star}=\frac{\gamma}{(1-\theta)^\delta\lambda^{1-\delta}}. \tag{A.6}$$

To derive $p_l^\star$, insert $l_2^\star$, $f^\star$ and $p_c^\star$ in Eq. (A.1b). Note that $p_{l_2}^\star=0$, as $l_2^\star>0$.

$$p_l^\star=p_c^\star(1-\delta)(1-\theta)^\delta\lambda^{-\delta}=\frac{\gamma(1-\delta)}{\lambda}. \tag{A.7}$$

Inserting $l_2^\star$, $f^\star$ and $p_c^\star$ in Eq. (A.1e) one derives for $p_f^\star$:

$$p_f^\star=\frac{p_c^\star\delta(1-\theta)^{\delta-1}\lambda^{1-\delta}}{\rho}=\frac{\gamma\delta}{\rho(1-\theta)}. \tag{A.8}$$

One derives $p_w^\star$ from Eq. (A.1a)

$$p_w^\star=p_f^\star-\frac{p_l^\star}{\alpha_1}=\gamma\left(\frac{\delta}{\rho(1-\theta)}-\frac{1-\delta}{\lambda\alpha_1}\right), \tag{A.9}$$

and finally $p_\theta^\star$ from Eq. (A.1f):

$$p_\theta^\star=p_w^\star\rho-\frac{1-\gamma}{w^\star}=\gamma\left(\frac{\delta}{1-\theta}-\frac{(1-\delta)\rho}{\lambda\alpha_1}\right)-\frac{1-\gamma}{\theta}. \tag{A.10}$$

A.2.2. *Interior solution*

In case of the interior solution, the restriction (10g) is not binding and thus $p_\theta^\star=0$, $w^\star>\theta$, $f^\star=1-w^\star$ and $b^\star=(w^\star-\theta)/(1-\theta)$. Inserting in Eq. (10b) yields $c^\star=(1-w^\star)^\delta\lambda^{1-\delta}$. From Eq. (A.1d) follows:

$$p_c^\star=\frac{\gamma}{c^\star}=\frac{\gamma}{(1-w^\star)^\delta\lambda^{1-\delta}}. \tag{A.11}$$

To derive $p_l^\star$, insert $l_2^\star$, $f^\star$ and $p_c^\star$ in Eq. (A.1b). Note that $p_{l_2}^\star=0$, as $l_2^\star>0$.

$$p_l^\star=p_c^\star(1-\delta)(1-w^\star)^\delta\lambda^{-\delta}=\frac{\gamma(1-\delta)}{\gamma}. \tag{A.12}$$

Inserting $l_2^\star$, $f^\star$ and $p_c^\star$ in Eq. (A.1e) one derives for $p_f^\star$:

$$p_f^\star = \frac{p_c^\star \delta (1-w^\star)^{\delta-1} \lambda^{1-\delta}}{\rho} = \frac{\gamma\delta}{\rho(1-w^\star)}. \tag{A.13}$$

One derives $p_w^\star$ from Eq. (A.1f):

$$p_w^\star = \frac{1-\gamma}{\rho w^\star}. \tag{A.14}$$

To determine $w^\star$, insert $p_l^\star$, $p_f^\star$ and $p_w^\star$ in Eq. (A.1a). This leads to the following quadratic equation for $w^\star$:

$$A w^{\star 2} + (B + C - A) w^\star - C = 0, \tag{A.15}$$

with $A = \gamma(1-\delta)\rho$, $B = \alpha_1 \delta \lambda \gamma$ and $C = \alpha_1 \lambda (1-\gamma)$. Hence, the positive solution for $w^\star$ is given by:

$$w^\star = \frac{-(B + C - A) + \sqrt{(B + C - A)^2 + 4AC}}{2A}. \tag{A.16}$$

A.3. *Numerical optimization*

All numerical optimizations were derived with the advanced optimal control software package MUSCOD-II (Diehl et al., 2001). The following exogenous parameters have been chosen for the numerical examples:

α_1	α_2	α_3	α_4	δ	β	λ	θ	ρ
0.025	1	1	0.2	0.7	1	1	0.25	0.03

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