# The relationship between intragenerational and intergenerational justice in the use of ecosystems and their services

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September 2, 2016

**Abstract:** Conflicts between intragenerational and intergenerational justice in the use of ecosystems and their services may arise in the design and implementation of sustainability policy. We present a model that depicts the relationship between intragenerational and intergenerational justice ('justice-relationship') against the backdrop of given ecological, economic and societal circumstances. These include the quality and quantity of ecosystem services, population development, substitutability of ecosystem services, technological progress, institutions for granting resource utilization rights, and political restrictions on redistribution. With this model, we numerically simulate how different assignments of resource utilization rights to potential ecosystem users impact on the justice-relationship depending on system determinants.

**Keywords:** ecological-economic model, efficiency, environmental justice, ecosystem services, equity, facilitation, distribution, independence, intragenerational, intergenerational, natural capital, rivalry, trade-off

**JEL-Classification:** D63, Q20, Q56, Q57

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# 1 Introduction

Realizing a sustainable use and conservation of ecosystems and their services is a major challenge for human society (MEA 2005, TEEB 2010a, UK-NEA 2011, UN 1992, UNEP 2012, Turnhout et al. 2012). Its implementation in global, national and local sustainability policy demands to account for the variety of *ecosystem services*. They can be provisioning, regulating, cultural or supporting services; substitutable and non-substitutable by human-made goods and services; rival or non-rival in consumption; excludable or non-excludable from use; consumptive or non-consumptive in terms of the natural capital from which they originate. Intragenerational trade-offs in the provision of different ecosystem services by one renewable resource stock (e.g. between wood provision and recreational services provided by a forest), as well as intergenerational trade-offs between the consumption of ecosystem services by today's persons and the conservation of renewable resource stocks for future persons (e.g. between present provision of agricultural goods and the maintenance of fertile soils for future agricultural production) may occur (cf. Rodríguez et al. 2006, TEEB 2010b: 81ff.). These potential trade-offs ask for careful recognition of the linkages between renewable resource stocks and the provision of multiple ecosystem services.

The societal objective of *sustainability* in the use of ecosystem services refers to two different justices of equal normative rank: *intragenerational justice* and *intergenerational justice*. In the design and implementation of sustainability policy, these two justices potentially conflict. Generally, three relationships in the attainment of the two justices ('justice relationships') occur in real-world contexts: independency, facilitation and rivalry (Glotzbach and Baumgärtner 2012, Baumgärtner et al. 2012).

Although considerable research has modeled problems of intergenerational justice in renewable resource use (specifically under the maximin-criterion in the spirit of Rawls' second principle of justice, e.g. Cairns and Tian 2010, Martinet 2007), less attention has been paid to the simultaneous investigation of intragenerational and intergenerational problems in renewable resource use (cf. e.g. Roemer and Veneziani 2007). In this paper, we introduce an ecological-economic model that provides the basis for a systematic investigation of the 'justice relationship' against the backdrop of given ecological, economic and societal circumstances. The model does not aim at a comprehensive analysis of justice, but focuses on environmental justice – that is, justice in the distribution of access rights to ecosystem services.

In the two-period ecological-economic model, human actors maximize their individual utility from a manufactured consumption good and two ecosystem services delivered by a renewable resource stock, a consumptive ecosystem service (i.e. a resource harvest) and a non-consumptive ecosystem service. The policy instrument (*instrument of justice*) is the assignment of first- and second-generation utilization rights to the renewable resource stock by a social planner. The given ecological, economic or societal circumstances (such as the available amount of renewable resource stock, the endowment with a numeraire good, the rate of technical progress, or political restrictions on the assignment of resource utilization rights) characterize a specific ecological-economic system and are – for the sake of this analysis – given *system determinants*. The degree of intragenerational (resp.: intergenerational) justice in ecosystem-service use is measured in terms of the Rawlsian Difference Principle regarding the individual utilities attained by the first-generation individuals (resp.: the first- and second-generation individuals). The ecological-economic model is a *generic* model – that is, it allows creating insights into the 'justice relationship' both at a general level for a large class of systems, and may be detailed for specific real-world systems (cf. Baumgärtner et al. 2008: 389f.).

Based on the generic ecological-economic model, we conduct initial steps of model analysis. First, we prove the plausibility of the model by analyzing how the model parameters (representing system determinants) and policy variables (representing instruments of justice) impact on the indirect utility functions of present and future individuals. The model parameters are the quantity of ecosystem services (i.e. the total endowment with the renewable resource stock and its intrinsic growth rate), the quality of ecosystem services (consumptivity, rivalry in consumption and excludability from consumption), population development, substitutability of ecosystem services (both between manufactured-good consumption and aggregate ecosystem-service consumption, and between a consumptive and a non-consumptive ecosystem service), technological progress (in the manufacturing sector and in resource harvesting), and political restrictions on the assignment of resource utilization rights; the policy variables are the individual resource utilization rights. Second, we define – in terms of the model – *efficiency* in the assignment of first- and second-generation resource utilization rights regarding the objectives of intragenerational and intergenerational environmental justice. Through numerical simulation, we identify efficient and inefficient assignments of resource utilization rights for a specific ecological-economic system, and illustrate how (*in*)*efficiency* is related to the occurrence of rivalry, independency and facilitation in the 'justice relationship'. Third, we illustrate based on a numerical simulation how the use of the *instrument of justice* (i.e. different assignments of first- and second-generation resource utilization rights) and a change in certain *system determinants* impact on the occurrence of rivalry, independency and facilitation in the 'justice relationship'. With these first steps of model analysis, we demonstrate that the model introduced here is a valuable tool to explore political paths that consistently and effectively improve on both intragenerational and intergenerational environmental justice.

The paper is organized as follows. In Section 2, we lay the normative foundation – by discussing environmental justice, the three possible relationships between intra- and intergenerational environmental justice, and their determinants. In Section 3, we introduce the ecological-economic model. In Section 4, we present the results of the model analysis. In Section 5, we discuss these results and conclude by identifying further research questions.

## 2 Normative foundations: environmental justice, determinants, and efficiency

In this paper, we apply the ideas of intragenerational and intergenerational justice to the use of ecosystems and their services. Whereas the 'classical' environmental justice discourse (cf. e.g. Schlosberg 2007) investigates the unequal distribution of environmental burdens and hazards between different contemporary societal groups, we more broadly assume that **environmental justice** is about "how environmental goods and bads are to be distributed among human beings, within and across societies at any one time, and between generations across time" (Baxter 2005: 6). A conception of environmental justice that specifically addresses the intragenerational and intergenerational distribution of access rights to ecosystem services is proposed by Sievers-Glotzbach (2013). We draw on this conception to derive model indicators for intragenerational and intergenerational environmental justice. The conception builds on John Rawls' "A Theory of Justice" (1971). It extends Rawls' impartial original position – by including representatives from the present and future generations as contract partners, and access rights to ecosystem services in Rawls' category of primary social goods – and, consequently, deduces a *principle of intragenerational* (resp.: *intergenerational*) *environmental justice*: Access rights to ecosystem services have to be distributed in such a way that they are to the greatest benefit of the least-advantaged members of the present generation (resp.: across the present and future generations) (Sievers-Glotzbach 2013). From these principles, we derive indicators that measure the degree of intragenerational and intergenerational environmental justice in the model system. The model indicators depict the 'benefit of the least-advantaged' in terms of individual utility.

In real-world systems, three '**justice relationships**' may hold in the attainment of intragenerational and intergenerational environmental justice (Glotzbach and Baumgärtner 2012: 337):

1. **Independency**: The objectives of intra- and intergenerational environmental justice can be achieved independently, that is, attaining one objective to a higher degree does not necessitate any change in the degree of attainment of the other objective.

2. **Facilitation**: Achieving one objective of environmental justice supports achieving the other one ("win-win"), that is, attaining one objective to a higher degree induces a higher degree of attainment of the other objective.

3. **Rivalry**: A fundamental rivalry ("trade-off") exists between the objectives of intra- and intergenerational environmental justice, that is, attaining one objec-

tive to a higher degree necessarily reduces the degree of attainment of the other objective.

All three relationships do not need to be symmetric (Baumgärtner et al. 2012: Notes 20, 22, 23): The achievement of one objective of justice may be independent, favorable resp. rival regarding the achievement of the other objective of justice, but not vice versa.

Independency, facilitation and rivalry in the 'justice relationship' hold true under different assumptions on certain **determinants** of the 'justice relationship' (Glotzbach and Baumgärtner 2012: Sec. 4). These *determinants* are the quantity of ecosystem services, the quality (i.e., rivalry in and excludability from use) of ecosystem services, population development, substitutability of ecosystem services by human-made goods and services, technological progress, institutions and political restrictions (ibid.). They were revealed as the result of a qualitative content analysis of the political and scientific sustainability discourse. The ecological-economic model serves to better understand how the determinants influence the occurrence and extent of rivalry, independency or facilitation in the 'justice relationship'. In the model, we differentiate the determinants in an *instrument of justice* and several *system determinants*: The *instrument of justice* is the assignment of first- and second-generation resource utilization rights by the social planner; the *system determinants* are the model parameters (such as the initial endowment with the renewable resource stock) which cannot be controlled by the social planner, but which are given for a specific ecological-economic system. In a numerical simulation, we investigate how the use of the instrument of justice and a change in certain system determinants, respectively, impact on the occurrence and extent of rivalry, independency or facilitation in the 'justice relationship'.

Further, the occurrence of rivalry, independency or facilitation in the 'justice relationship' is related to the condition of **(in)efficiency** (Baumgärtner et al. 2012). The use of instruments of justice is defined to be efficient if it is not possible in a given system to better attain one objective of justice without worsening the attainment of the other objective of justice (ibid. 6). Hence, efficiency assesses the use of instruments of justice in terms of attaining the two objectives of intra- and intergenerational environmental justice within a community. The three 'justice relationships' are related to efficiency as follows: An efficient use of the instruments of justice implies a 'justice relationship' of rivalry; an inefficient use of the instruments of justice implies a 'justice relationship' of facilitation or independence (ibid. 8). Because of this relation, we define efficiency in terms of the ecological-economic model and identify by method of numerical simulation efficient and inefficient assignments of resource utilization rights for a specific ecological-economic system.

# 3 Model

There are two time periods $t = 1, 2$ and two non-overlapping generations. Generation 1 lives at time $t = 1$ and comprises two individuals $A$ and $B$; generation 2 lives at time $t = 2$ and comprises $2n$ identical individuals $C$, where $n > 0$ is the population growth factor, so that $n = 1$ ($n > 1$, $n < 1$) means a constant (growing, shrinking) population size.

There are four goods: a manufactured consumption good, a renewable resource stock (e.g. a forest stand), a provisioning ecosystem service which is consumptive, i.e. the harvest of which diminishes the resource stock (e.g. timber provision), and a non-consumptive ecosystem service. The manufactured consumption good and the consumptive ecosystem service are private goods. As for the non-consumptive ecosystem service, we study two alternative variants of the model: (a) the ecosystem service is a private good characterized by intragenerational rivalry in, and excludability from, consumption (e.g. provision of non-timber forest products such as fruits, berries, mushrooms etc.); (b) the ecosystem service is a pure public good characterized by intragenerational non-rivalry in, and non-excludability from, consumption (e.g. a regulating service such as erosion control or climate regulation, or a cultural service such as aesthetic satisfaction or recreation). Let the parameter $\nu \in \{0, 1\}$ denote the degree of rivalry/excludability, where $\nu = 1$ ($\nu = 0$) means that the non-consumptive ecosystem service is a pure private good (public good).

The manufactured consumption good is exogenously provided. At $t = 1$, the total endowment is $Y_1 > 0$, and each individual $i$ consumes an equal share:

$$Y^i = \frac{Y_1}{2} \qquad \text{for } i = A, B \ . \tag{1}$$

Due to autonomous technological progress in the manufacturing sector, the total endowment with the manufactured consumption good increases by a factor $\mu > 0$ from $t = 1$ to $t = 2$. Hence, the amount of the manufactured good consumed by individual $C$ in $t = 2$ is given by

$$Y^C = \frac{\mu Y_1}{2n} \ . \tag{2}$$

Initially, i.e. at $t = 1$, there is a total endowment $R_1 > 0$ with the renewable resource stock. Individual $i$ (with $i = A, B$) possesses utilization rights to an amount $R^i \geq 0$ of the resource stock with

$$R^A + R^B \leq R_1 \ . \tag{3}$$

He harvests an amount $H^i$ of the consumptive ecosystem service by means of a linear harvest technology that converts one unit of the resource stock $R^i$ into one unit of $H^i$, subject to

$$0 \leq H^i \leq R^i \qquad \text{for } i = A, B \ . \tag{4}$$

The non-consumptive ecosystem service $S^i$ is provided by the non-converted resource stock in proportion to the stock size:

$$S^i = R^i - H^i + (1 - \nu)\left(R_1 - R^i - H^j\right) \qquad \text{for } i = A, B, \ j \neq i \ . \tag{5}$$

According to Equation (5), if (a) the non-consumptive ecosystem service is a private good, $\nu = 1$, $S^i$ is provided by the non-converted resource stock possessed by individual $i$ (with $i = A, B$): $S^i = R^i - H^i$. If (b) the non-consumptive ecosystem service is a pure public good, $\nu = 0$, $S^i$ is provided by the total of the non-converted resource stock in $t = 1$: $S^i = R_1 - (H^A + H^B)$.

The non-converted resource stock naturally regenerates with an intrinsic resource growth factor $\omega > 0$. The special case $\omega = 1$ characterizes a non-renewable resource with simple cake-eating-dynamics. As harvest of $H^i$ does diminish the resource stock, but consumption of $S^i$ does not, the total resource stock $R_2$ in $t = 2$ depends on the harvested amount $H^A + H^B$ of the consumptive ecosystem service in $t = 1$:

$$R_2 = \omega \left(R_1 - H^A - H^B\right) \ . \tag{6}$$

At time $t = 2$, representative individual $C$ of generation 2 possesses utilization rights to an amount $R^C \geq 0$ of the remaining resource stock with

$$R^C \leq \frac{R_2}{2n} \ . \tag{7}$$

He harvests an amount $H^C$ of the consumptive ecosystem service. Due to autonomous technical progress in the harvest technology, he can convert one unit of the resource stock $R^C$ into $\gamma > 0$ units of $H^C$. If $\gamma > 1$, the resource efficiency of the linear harvest technology improves from $t = 1$ to $t = 2$, that is, a greater amount of the consumptive ecosystem service can be harvested through converting the same amount of the resource stock. Hence, harvesting in $t = 2$ is subject to

$$0 \leq H^C \leq \gamma R^C \ . \tag{8}$$

The level of the non-consumptive ecosystem service, $S^C$, is given by

$$S^C = R^C - \frac{H^C}{\gamma} + (1 - \nu) \left[R_2 - R^C - (2n - 1)\frac{H^C}{\gamma}\right] \ . \tag{9}$$

According to Equation (9), if (a) the non-consumptive ecosystem service is a private good, $\nu = 1$, $S^C$ is provided by the non-converted resource stock possessed by the representative individual $C$: $S^C = R^C - H^C/\gamma$; if (b) the non-consumptive ecosystem service is a pure public good, $\nu = 0$, $S^C$ is provided by the total of the non-converted resource stock in $t = 2$: $S^C = R_2 - 2nH^C/\gamma$.

Individual $i$ (with $i = A, B, C$) has preferences for the consumption of the manufactured consumption good $Y^i$, the consumptive ecosystem service $H^i$ and the non-consumptive ecosystem service $S^i$ as represented by the utility function

$$\begin{aligned} U^i = U(Y^i, H^i, S^i) &= \left[(1-\alpha)\left(Y^i\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(E^i(H^i, S^i)\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \\ \text{with } E^i(H^i, S^i) &= \left[\beta\left(H^i\right)^{\frac{\theta-1}{\theta}} + (1-\beta)\left(S^i\right)^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}} \ , \\ &\quad \text{where } 0 < \alpha, \beta < 1 \ . \end{aligned} \tag{10}$$

In this nested CES-utility function, overall utility is characterized by a constant elasticity of substitution $\sigma > 0$ between the manufactured consumption good, $Y^i$, and the utility from aggregate ecosystem-service consumption, $E^i$; and the utility from aggregate ecosystem-service consumption is characterized by a constant elasticity of substitution $\theta > 0$ between the consumptive and the non-consumptive ecosystem service, $H^i$ and $S^i$. For $\theta \to 0$ ($\theta \to \infty$), the consumptive and the non-consumptive ecosystem service are perfect complements (substitutes) in consumption. For $\sigma \to 0$ ($\sigma \to \infty$), the manufactured good and aggregate ecosystem services are perfect complements (substitutes) in consumption. At both levels of utility, the special case of a Cobb-Douglas function obtains for $\sigma \to 1$ viz. $\theta \to 1$. The parameter $\alpha$ measures the importance of aggregate ecosystem services relative to manufactured goods consumption for overall utility; the parameter $\beta$ measures the importance of the consumptive ecosystem service relative to the non-consumptive ecosystem service for aggregate ecosystem services consumption.

Individual $i$ chooses the levels of $H^i$ and $S^i$ so as to maximize his individual utility (Equation 10) subject to ecological, technological and institutional feasibility:

$$\max_{H^i,S^i} U^i = U(Y^i, H^i, S^i) \quad \text{subject to (1), (4), (5)} \quad \text{for } i = A, B \; , \tag{11}$$

$$\max_{H^C,S^C} U^C = U(Y^C, H^C, S^C) \quad \text{subject to (2), (6), (8), (9)} \; . \tag{12}$$

In variant (a) of the model, where the non-consumptive ecosystem service is a private good, the maximization problems (11) of individuals $A$ and $B$ are independent of each other, and the maximization problems (12) of individuals $C$ are independent of each other. In contrast, in variant (b) of the model, where the non-consumptive ecosystem service is a public good, the maximization problems (11) of individuals $A$ and $B$ are interdependent through constraint (5) on how the amount of the public ecosystem service depends on the non-converted resource stock; likewise the maximization problems (12) of individuals $C$ are interdependent through constraint (9). For this case, we assume that all individuals of the same generation act simultaneously and the solution is the Nash equilibrium of the non-cooperative game. The solution to optimization problems (11) and (12), i.e. the individually optimal extent of ecosystem service consumption for a given vector $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$ of resource utilization rights, is denoted by $H^{i\star}(\boldsymbol{R})$ and

$S^{i\star}(\boldsymbol{R})$. Individual $i$ thus achieves the utility level

$$V^i(\boldsymbol{R}) = U\left(Y^i, H^{i\star}(\boldsymbol{R}), S^{i\star}(\boldsymbol{R})\right) \quad \text{for } i = A, B, C \ , \tag{13}$$

where $V^i(\cdot)$ is the indirect utility function derived from utility function (10) through optimization problem (11) (for $i = A, B$) viz. (12) (for $i = C$) for given resource utilization rights $\boldsymbol{R}$.

A social planner assigns first- and second-generation utilization rights $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$ with the objective of achieving a maximum of intragenerational and intergenerational environmental justice and taking into account individuals' optimizing behavior (11, 12, 13). The ideal of intragenerational and of intergenerational environmental justice – as derived from the Rawlsian Difference Principle (cf. Section 2) – is achieved by choosing $\boldsymbol{R}$ so as to maximize the minimum actually realized utility level $V^i$ of individuals $i = A, B$, and of individuals $i = A, B, C$, respectively:

$$\max_{\boldsymbol{R}} \ AJ(\boldsymbol{R}) \quad \text{and} \quad \max_{\boldsymbol{R}} \ EJ(\boldsymbol{R}) \tag{14}$$

where

$$AJ(\boldsymbol{R}) = \min \left\{V^A(\boldsymbol{R}), V^B(\boldsymbol{R})\right\} \tag{15}$$

$$EJ(\boldsymbol{R}) = \min \left\{V^A(\boldsymbol{R}), V^B(\boldsymbol{R}), V^C(\boldsymbol{R})\right\} \tag{16}$$

are indicators for intragenerational environmental justice and for intergenerational environmental justice, respectively, for a given distribution of resource utilization rights $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$. In assigning resource utilization rights, the social planner is limited by physical feasibility as given by equations (3), (6) and (7), by a political constraint on intragenerational distribution within generation 1,

$$\underline{\chi} \le \frac{R^A}{R^B} \le \overline{\chi} \ , \tag{17}$$

by a political constraint on intergenerational distribution,

$$\underline{\pi} \le R^A + R^B \le \overline{\pi} \ , \tag{18}$$

and by a political constraint on access to the remaining resource stock by generation 2,

$$\underline{\xi} \le R^C \le \overline{\xi} \ . \tag{19}$$

The exact time structure of decision making is as follows. At $t = 0$, the social planner assigns resource utilization rights $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$ to members of generations 1 and 2. At $t = 1$, first-generation individuals $i = A, B$ maximize their utility $U^i$ (optimization problem 11). At $t = 2$, second-generation individuals $C$ maximize their utility $U^C$ (optimization problem 12).

In this model, the six *determinants* of the relationship between intragenerational and intergenerational justice in the use of ecosystem services (cf. Section 2) are captured by the following model parameters and variables: "institutions" are described by the assignment of utilization rights $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$. The "quality of ecosystem service" is described by the distinction between the consumptive ecosystem service and the non-consumptive ecosystem service, and by the degree $\nu$ of rivalry in, and excludability from, consumption of the non-consumptive ecosystem service. The "quantity of ecosystem service" is described by the initial endowment $R_1$ with the renewable resource stock and its intrinsic growth factor $\omega$. The "population development" is described by the population growth factor $n$. The "substitutability of the ecosystem service" is described by the parameters $\sigma$, which measures substitutability between manufactured-good consumption and aggregate ecosystem-service consumption, and $\theta$, which measures substitutability between the consumptive and the non-consumptive ecosystem service. The "technological development" is described by the factors $\mu$ and $\gamma$ of technological progress in the manufacturing sector and in resource harvesting, respectively. The "political restrictions" are described by constraints (17), (18) and (19) on the intra- and intergenerational assignment of resource utilization rights by the social planner.

# 4 Analysis and results

In the following model analysis, we proceed in four steps. First, we analytically derive the general model solutions for model variants (a) and (b), respectively (Section 4.1). Second, we analyze the impact of each model parameter on the indirect utility functions of present and future individuals using the method of comparative statics (Section 4.2). Third, we define the normative objective of efficiency (Section 4.3). Fourth, we assess the model solutions in terms of efficiency for a specific ecological-economic system, and study the impact of variations in parameter values, using the method of numerical simulation (Section 4.4).

## 4.1 Analytical model solution

### 4.1.1 Model variant (a): The non-consumptive ecosystem service $S^i$ is a private good ($\nu = 1$)

In variant (a) of the model, where the non-consumptive ecosystem service is a private good, the maximization problems (11) of individuals $A$ and $B$ are independent of each other, and the maximization problems (12) of individuals $C$ are independent of each other. As a result, the individually optimal solution $S^{i\star}$ and $H^{i\star}$ for individual $i$ (for $i = A, B, C$), and, consequently, also this individual's indirect utility function $V^i$, depends only on the resource utilization right $R^i$ of that individual $i$:

$$H^{i\star}(\boldsymbol{R}) = \left[1 + \left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R^i \quad \text{for } i = A, B \tag{20}$$

$$S^{i\star}(\boldsymbol{R}) = \left[1 + \left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1} R^i \quad \text{for } i = A, B \tag{21}$$

$$V^{i}(\boldsymbol{R}) = \left[(1-\alpha)\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\left[\beta^{\theta} + (1-\beta)^{\theta}\right]^{\frac{1}{\theta-1}} R^i\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \quad \text{for } i = A, B \tag{22}$$

$$H^{C\star}(\boldsymbol{R}) = \left[\gamma^{-1} + \gamma^{-\theta}\left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R^i \tag{23}$$

$$S^{C\star}(\boldsymbol{R}) = \left[1 + \gamma^{\theta-1}\left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1} R^i \tag{24}$$

$$V^{C}(\boldsymbol{R}) = \left[(1-\alpha)\left(\frac{\mu Y_1}{2n}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\left[\beta^{\theta}\gamma^{\theta-1} + (1-\beta)^{\theta}\right]^{\frac{1}{\theta-1}} R^C\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{25}$$

*Proof.* See Appendix A.1. □

#### 4.1.2 Model variant (b): The non-consumptive ecosystem service $S^i$ is a public good ($\nu = 0$)

If the non-consumptive ecosystem service $S^i$ is a public good ($\nu = 0$), the maximization problems (11) of individuals $A$ and $B$ are interdependent through constraint(5) on how the amount of the public ecosystem service depends on the non-converted resource stock; likewise the maximization problems (12) of individuals $C$ are interdependent through constraint (9). Assuming that all individuals of the same generation act simultaneously and the solution is the Nash equilibrium of the non-cooperative game, one obtains that in generation 1 as well as in generation 2 a unique and stable Nash equilibrium exists.

In generation 1, three cases need to be distinguished, depending on whether resource utilization rights $R^i$ are a binding constraint for both individuals $A$ and $B$, for only one of them, or for none.

**Case 1-I.** For $R^i \geq \left[2 + \left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R_1$ (with $i = A, B$), i.e. if in the optimal solution resource utilization rights $R^i$ are not a binding constraint for any of the two individuals, the model has the following symmetric solution for generation 1 ($i = A, B$):

$$H^{i\star}(\boldsymbol{R}) = \left[2 + \left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R_1 \tag{26}$$

$$S^{i\star}(\boldsymbol{R}) = \left[1 + 2\left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1} R_1 \tag{27}$$

$$V^i(\boldsymbol{R}) = \left[(1-\alpha)\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\frac{\left[\beta^{\theta} + (1-\beta)^{\theta}\right]^{\frac{\theta}{\theta-1}}}{2\beta^{\theta} + (1-\beta)^{\theta}} R_1\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{28}$$

$$R_2 = \omega\left[1 + 2\left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1} R_1 \tag{29}$$

In this case, the optimal solution for generation 1 does, in effect, not depend on individual resource utilization rights $R^i$, as these are not a binding constraint.

**Case 1-II.** For $R^i < \left[2 + \left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R_1$ (with $i = A, B$), i.e. if in the optimal solution resource utilization rights $R^i$ are a binding constraint for both individuals, the model has the following symmetric solution for generation 1 ($i, j = A, B$ and $j \neq i$):

$$
\begin{aligned}
H^{i\star}(\boldsymbol{R}) &= R^i && (30)\\
S^{i\star}(\boldsymbol{R}) &= R_1 - R^i - R^j && (31)\\
V^i(\boldsymbol{R}) &= \left[(1-\alpha)\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\beta R^{i\,\frac{\theta-1}{\theta}} + (1-\beta)\left(R_1 - R^i - R^j\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} && (32)\\
R_2 &= \omega\left(R_1 - R^i - R^j\right) && (33)
\end{aligned}
$$

**Case 1-III.** For an asymmetric assignment of resource utilization rights of $R^i \geq \left[2 + \left(\frac{1}{\beta} - 1\right)^\theta\right]^{-1} R_1$ and $R^j < \left[2 + \left(\frac{1}{\beta} - 1\right)^\theta\right]^{-1} R_1$ (with $i, j = A, B$ and $j \neq i$), i.e. if in the optimal solution resource utilization rights are a binding constraint for individual $j$ but not for individual $i$, the model has the following general solution for generation 1 ($i, j = A, B$ and $j \neq i$):

$$
\begin{aligned}
H^{i\star}(\boldsymbol{R}) &= \left[1 + \left(\frac{1}{\beta} - 1\right)^\theta\right]^{-1}\left(R_1 - R^j\right) && (34)\\
H^{j\star}(\boldsymbol{R}) &= R^j && (35)\\
S^{i\star}(\boldsymbol{R}) = S^{j\star}(\boldsymbol{R}) &= \left[1 + \left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1}\left(R_1 - R^j\right) && (36)\\
V^i(\boldsymbol{R}) &= \left[(1-\alpha)\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\left[\beta^\theta + (1-\beta)^\theta\right]^{\frac{1}{\theta-1}}\left(R_1 - R^j\right)\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} && (37)\\
V^j(\boldsymbol{R}) &= \Bigg[(1-\alpha)\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\Bigg\{\beta R^{j\,\frac{\theta-1}{\theta}} + \\
&\qquad (1-\beta)\left(\left[1 + \left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1}\left(R_1 - R^j\right)\right)^{\frac{\theta-1}{\theta}}\Bigg\}^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\Bigg]^{\frac{\sigma}{\sigma-1}} && (38)\\
R_2 &= \omega\left[1 + \left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1}\left(R_1 - R^j\right) && (39)
\end{aligned}
$$

In generation 2, two cases need to be distinguished, depending on whether or not resource utilization rights $R^C$ are a binding constraint for individual $C$. In each case, $R_2$ is given by either (29) or (33) or (39), depending on the first-generation solution.

**Case 2-I.** For $R^C \geq \left[2n + \gamma^{1-\theta}\left(\frac{1}{\beta}-1\right)^{\theta}\right]^{-1} R_2$, i.e. if in the optimal solution resource utilization rights $R^C$ are not a binding constraint for individual $C$, the model has the following general solution for generation 2:

$$H^{C\star}(\boldsymbol{R}) = \left[2n\gamma^{-1} + \gamma^{-\theta}\left(\frac{1}{\beta} - 1\right)^{\theta}\right]^{-1} R_2 \tag{40}$$

$$S^{C\star}(\boldsymbol{R}) = \left[1 + 2n\gamma^{\theta-1}\left(\frac{1}{\beta} - 1\right)^{-\theta}\right]^{-1} R_2 \tag{41}$$

$$V^{C}(\boldsymbol{R}) = \left[(1-\alpha)\left(\frac{\mu Y_1}{2n}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left(\gamma\frac{\left[\beta^{\theta} + \gamma^{1-\theta}(1-\beta)^{\theta}\right]^{\frac{\theta}{\theta-1}}}{2n\beta^{\theta} + \gamma^{1-\theta}(1-\beta)^{\theta}} R_2\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{42}$$

**Case 2-II.** For $R^C < \left[2n + \gamma^{1-\theta}\left(\frac{1}{\beta}-1\right)^{\theta}\right]^{-1} R_2$, i.e. if in the optimal solution resource utilization rights $R^C$ are a binding constraint for individual $C$, the model has the following general solution for generation 2:

$$H^{C\star}(\boldsymbol{R}) = \gamma R^C \tag{43}$$

$$S^{C\star}(\boldsymbol{R}) = R_2 - 2nR^C \tag{44}$$

$$V^{C}(\boldsymbol{R}) = \left[(1-\alpha)\left(\frac{\mu Y_1}{2n}\right)^{\frac{\sigma-1}{\sigma}} + \alpha\left\{\beta\left(\gamma R^C\right)^{\frac{\theta-1}{\theta}} + (1-\beta)\left(R_2 - 2nR^C\right)^{\frac{\theta-1}{\theta}}\right\}^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{45}$$

*Proof.* See Appendix A.2. □

## 4.2 Impact of model parameters on the indirect utility functions

This subsection describes the impact of the model parameters – that is, the initial endowment $Y_1$ with the manufactured consumption good, the initial endowment $R_1$ with the renewable resource stock, the individual resource utilization right $R^i$ (for $i = A, B, C$) to the renewable resource stock, the intrinsic growth factor $\omega$ of the renewable resource stock, the population growth factor $n$, the elasticities of substitution $\theta$ and $\sigma$, the factors $\mu$ and $\gamma$ of technological progress in the manufacturing sector and in resource harvesting – on the indirect utility functions $V^i$ (for $i = A, B, C$). A marginal increase in the value of the respective model parameter implies a marginal increase (+), decrease (−) or no change (0) in the value of the indirect utility functions for the respective model variants (MV) as specified in Table 1.

Table 1: Impact of a marginal increase in the value of the particular model parameter on the values of $V^i$ (for $i = A, B, C$).

<table>
<tr><th rowspan="3">Model parameter</th><th colspan="13">Impact of model parameter on $V^i$ (for $i = A, B$) and $V^C$</th></tr>
<tr><th colspan="2">MV (a)</th><th colspan="3">MV (b1)</th><th colspan="4">MV (b2)</th><th colspan="3">MV (b3)</th></tr>
<tr><th>$V^i$</th><th>$V^C$</th><th>$V^i$</th><th colspan="2">$V^C$</th><th>$V^i$</th><th>$V^j$</th><th colspan="2">$V^C$</th><th>$V^i$</th><th colspan="2">$V^C$</th></tr>
<tr><td>$Y_1$</td><td>+</td><td>+</td><td>+</td><td colspan="2">+</td><td>+</td><td>+</td><td colspan="2">+</td><td>+</td><td colspan="2">+</td></tr>
<tr><td>$R_1$</td><td>0</td><td>0</td><td>+</td><td colspan="2">+</td><td>+</td><td>+</td><td colspan="2">+</td><td>+</td><td colspan="2">+</td></tr>
<tr><td>$R^i\,(i = A, B)$</td><td>+</td><td>0</td><td>0</td><td colspan="2">0</td><td>+</td><td>–</td><td colspan="2">–</td><td>+</td><td colspan="2">–</td></tr>
<tr><td>$R^C$</td><td>0</td><td>+</td><td>0</td><td>0</td><td>+</td><td>0</td><td>0</td><td>0</td><td>+</td><td>0</td><td>0</td><td>+</td></tr>
<tr><td></td><td>0</td><td>0</td><td>0</td><td colspan="2">+</td><td>0</td><td>0</td><td colspan="2">+</td><td>0</td><td colspan="2">+</td></tr>
<tr><td>$n$</td><td>0</td><td>–</td><td>0</td><td>–*</td><td>–</td><td>0</td><td>0</td><td>–*</td><td>–</td><td>0</td><td>–*</td><td>–</td></tr>
<tr><td></td><td>–</td><td>–**</td><td>–</td><td colspan="2">–</td><td>–</td><td>–</td><td colspan="2">–</td><td>–</td><td colspan="2">–</td></tr>
<tr><td></td><td>–</td><td>–</td><td>–</td><td colspan="2">–</td><td>–</td><td>–</td><td colspan="2">–</td><td>–</td><td colspan="2">–</td></tr>
<tr><td></td><td>0</td><td>+</td><td>0</td><td colspan="2">+</td><td>0</td><td>0</td><td colspan="2">+</td><td>0</td><td colspan="2">+</td></tr>
<tr><td></td><td>0</td><td>+*</td><td>0</td><td>+*</td><td>+</td><td>0</td><td>0</td><td>+*</td><td>+</td><td>0</td><td>+*</td><td>+</td></tr>
</table>

*Explanation*: $\star$ holds for $\theta < 1$, $\star\star$ holds for $\sigma > 1$.

*Proof.* See Appendix A.3 for model variant (a), Appendix A.4 for model variant (b). □

The non-shaded cells in Table 1 indicate solutions obtained by comparative statics; the grey-shaded cells indicate solutions obtained by numerical simulation. As there are two general model solutions in the model variants (b-1-I), (b-1-III/b2) and (b-1-II/b3) (cf. Section 4.1), the left cell refers to general model solution 2-I and the right cell refers to general model solution 2-II, respectively. If the impact of the model parameters on both of the general model solutions is the same in terms of (+), (−) and 0, the impact is indicated in a single cell.

The results regarding the impact of the respective model parameters on the indirect utility functions (as presented in Table 1) indicate the plausibility of the introduced ecological-economic model.

## 4.3 Definition and analysis of efficiency

Referring to a classical definition of *economics* by Robbins (1932: 15),[1] we generally understand *efficiency* as non-wastefulness in the use of "scarce means" that have alternative uses to attain societally desired "ends". With multiple societal objectives, the efficiency of an allocation can be captured as non-dominance with respect to these normative considerations – in structural analogy to the criterion of Pareto-efficiency (Sen 1979, 1985). Accordingly, LeGrand (1990: 559) posits that efficiency refers to primary "social objectives".

Taking up the definition of efficiency by LeGrand (1990: 559) and following Baumgärtner et al. (2012: 6), we define the use of instruments of justice to be efficient if it is not possible in a given system to better attain one primary social objective without worsening the attainment of the other primary social objective. In the model, the primary social objectives are intragenerational and intergenerational environmental justice. We presume that the two justices are normative objectives of equal rank regarding societal desirability. In terms of the formal model (Section 3), we define efficiency as follows.[2]

**Definition 1**

A feasible assignment $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$ of resource utilization rights is *efficient* if and

[1] "Economics is the science which studies human behaviour as a relationship between [given] ends and scarce means which have alternative uses" (Robbins 1932: 15).

[2] In this definition, it is a regulation, i.e. an assignment of resource utilization rights $\boldsymbol{R}$, that is defined to be efficient and not an allocation $(H^A, S^A, H^B, S^B, H^C, S^C)$ – which is the usual entity to be defined as efficient.

only if there exists no other feasible assignment $\boldsymbol{R'} = \left(R^{A'}, R^{B'}, R^{C'}\right)$ for which

$$AJ(\boldsymbol{R'}) > AJ(\boldsymbol{R}) \quad \text{and} \quad EJ(\boldsymbol{R'}) \geq EJ(\boldsymbol{R})$$

or

$$EJ(\boldsymbol{R'}) > EJ(\boldsymbol{R}) \quad \text{and} \quad AJ(\boldsymbol{R'}) \geq AJ(\boldsymbol{R}).$$

Here, an assignment of resource utilization rights $\boldsymbol{R} = \left(R^A, R^B, R^C\right)$ is *feasible* if the social planner can implement the assignment subject to physical feasibility (Equations 3, 6 and 7) and political feasibility (Equations 17, 18 and 19). The set of all feasible assignments of resource utilization rights is the policy set.

The normative criterion of efficiency considered here is different from the criterion of 'Pareto-efficiency'[3] which is commonly used in economics. Whereas 'Pareto-efficiency' assesses allocations in terms of the well-being of individual persons, efficiency as considered here assesses the use of instruments of justice in terms of attaining the two objectives of intra- and intergenerational environmental justice. As this criterion of efficiency is derived from the Rawlsian difference principle, which involves a maximin-optimization, the relation between $V^i(\boldsymbol{R})$ for $i = A, B, C$ and $AJ(\boldsymbol{R})$ resp. $EJ(\boldsymbol{R})$ is nontrivial – and, hence, there exists no trivial connection between *efficiency* and 'Pareto-efficiency'. 'Pareto-efficiency' is not relevant to assess the *policy set* in terms of environmental justice. Thus, we focus on efficiency in the following numerical analysis.

## 4.4 Numerical simulation

To illustrate efficiency in terms of the model, we depict the outcomes of different feasible assignments of resource utilization rights $(R^A, R^B, R^C)$ in terms of intra- and intergenerational environmental justice for a specific ecological-economic system – that is, for specific parameter values of the system determinants $Y_1$, $R_1$, $n$, $\omega$, $\mu$, $\gamma$, $\alpha$, $\beta$, $\sigma$, $\theta$, $\underline{\chi}$, $\overline{\chi}$, $\underline{\pi}$, $\overline{\pi}$, $\underline{\xi}$, $\overline{\xi}$.

[3] According to the original criterion of efficiency by Vilfredo Pareto (1906), an allocation is 'Pareto-efficient' if it is not possible in a given system to improve on one person's individual utility without worsening the individual utility of any other person.

Figure 1 shows for the two model variants (a) (non-consumptive ecosystem service is a private good, $\nu = 1$, in blue) and (b) (non-consumptive ecosystem service is a public good, $\nu = 0$, in red) the *justice possibility set* in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for standard parameter values ($Y_1 = 1000$, $R_1 = 800$, $n = \omega = \mu = \gamma = 1$, $\alpha = \beta = 0.5$, $\sigma = \theta = 1$, $\underline{\chi} = \underline{\pi} = \underline{\xi} = 0$ so that they are not binding, and $\overline{\chi}$, $\overline{\pi}$, $\overline{\xi}$ so large that they are not binding). The horizontal axis measures AJ; the vertical axis measures EJ. Each point in the diagram represents the outcome of a specific assignment of resource utilization rights $(R^A, R^B, R^C)$. All outcomes that emerge from a feasible assignment of resource utilization rights constitute the justice possibility set.

All outcomes on the northeast frontier of the justice possibility set constitute the *justice possibility frontier* (JPF). The area on and to the southwest of the JPF-curve indicates the set of feasible outcomes in the given context ('opportunity set') – that is, for given system determinants. Outcomes outside of the JPF-curve are not feasible in the given context. All outcomes on the JPF-curve between points A and B in Figure 1, respectively, indicate efficient assignments of resource utilization rights: From these outcomes a higher degree of one justice cannot be attained without worsening the degree of attainment of the other justice. All other outcomes on and below the JPF-curve indicate inefficient assignments of resource utilization rights.

In all efficient outcomes, rivalry between intragenerational and intergenerational environmental justice necessarily occurs (Baumgärtner et al. 2012: 8). An example is outcome C in Figure 1: Improving on EJ from this point would necessarily reduce the degree of attainment of AJ, and vice versa. In all inefficient outcomes, either independency or facilitation between intragenerational and intergenerational environmental justice occurs (Baumgärtner et al. 2012: 8). For instance, in outcome D in Figure 1 there is facilitation between the two justices: As outcome D is located on the JPF-curve, improving on EJ from this point necessarily also increases the degree of AJ.[4] In outcome

[4]This facilitation is not symmetric: improving on AJ from point E does not necessarily also increase the degree of EJ.

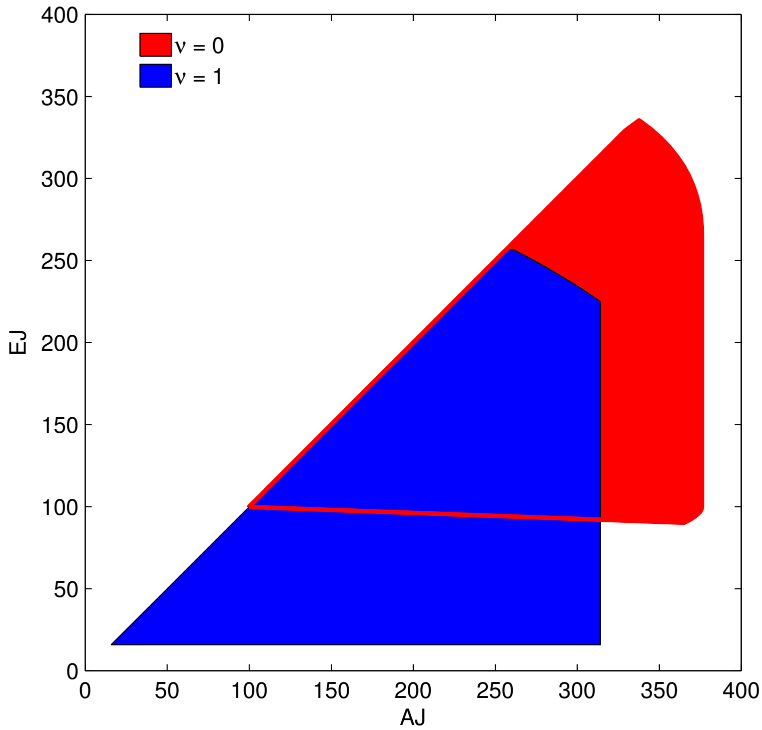



Figure 1: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for model variant (a) where the non-consumptive ecosystem service is a private good ($\nu = 1$, in blue) and for model variant (b) where the non-consumptive ecosystem service is a public good ($\nu = 0$, in red). Parameter values: $Y_1 = 1000$, $R_1 = 800$, $n = \omega = \mu = \gamma = 1$, $\alpha = \beta = 0.5$, $\sigma = \theta = 1$, $\underline{\chi} = \underline{\pi} = \underline{\xi} = 0$, $\overline{\chi} = \overline{\pi} = \overline{\xi} = \infty$.

E in Figure 1 there is independency between the two justices: Improving on AJ from outcome E does not necessitate any change in the degree of attainment of EJ, and vice versa.

A change in the system determinants will alter the opportunity set and therewith the shape of the JPF-curve (Baumgärtner et al. 2012: 8). In the following, we discuss for each system determinant how variation of the respective parameter value, for given standard values of the other parameters ($Y_1 = 1000$, $R_1 = 800$, $n = \omega = \mu = \gamma = 1$, $\alpha = \beta = 0.5$, $\sigma = \theta = 1$, $\underline{\chi} = \underline{\pi} = \underline{\xi} = 0$ so that they are not binding, and $\overline{\chi}$, $\overline{\pi}$, $\overline{\xi}$ so large that they are not binding; Figure 1), affects the picture.

Figure 2 shows the effect of variation in the initial endowment with the renewable ecosystem resource, $R_1$, with parameter values of $R_1$ ranging from 100 to 2000.

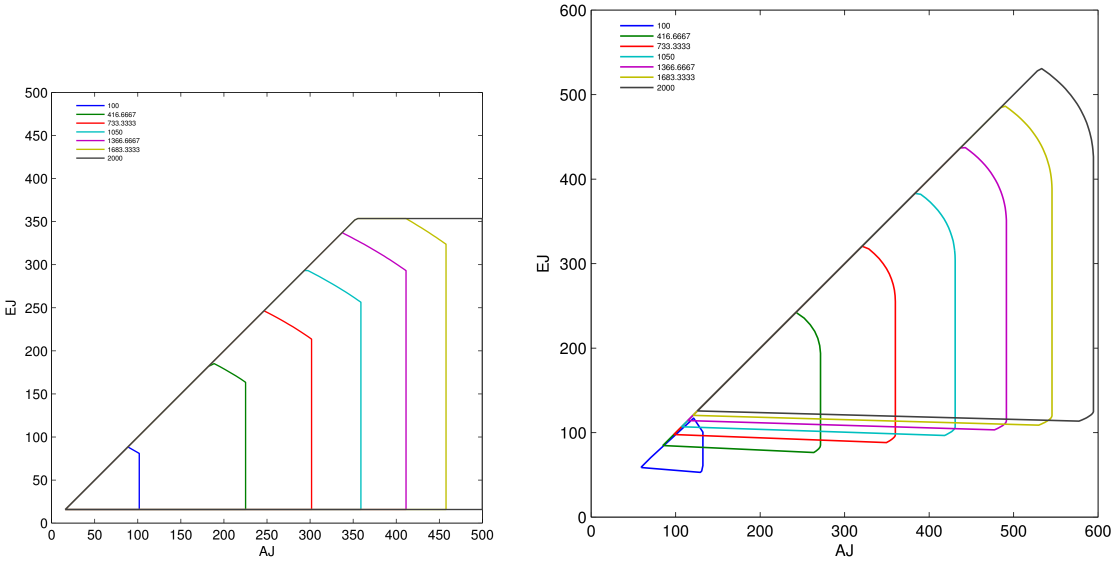



Figure 2: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the initial endowment with the renewable ecosystem resource, $R_1$, ranging from 100 to 2000, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

Figure 3 shows the effect of variation in the intrinsic resource growth factor, $\omega$, with parameter values of $\omega$ ranging from 0.5 to 2.5.

Figure 4 shows the effect of variation in the factor of technological progress in the resource harvesting sector, $\gamma$, with parameter values of $\gamma$ ranging from 0.5 to 2.5.

Figure 5 shows the effect of variation in the initial endowment with the manufactured good, $Y_1$, with parameter values of $Y_1$ ranging from 100 to 2000.

Figure 6 shows the effect of variation in the factor of technological progress in the manufacturing sector, $\mu$, with parameter values of $\mu$ ranging from 0.5 to 2.5.

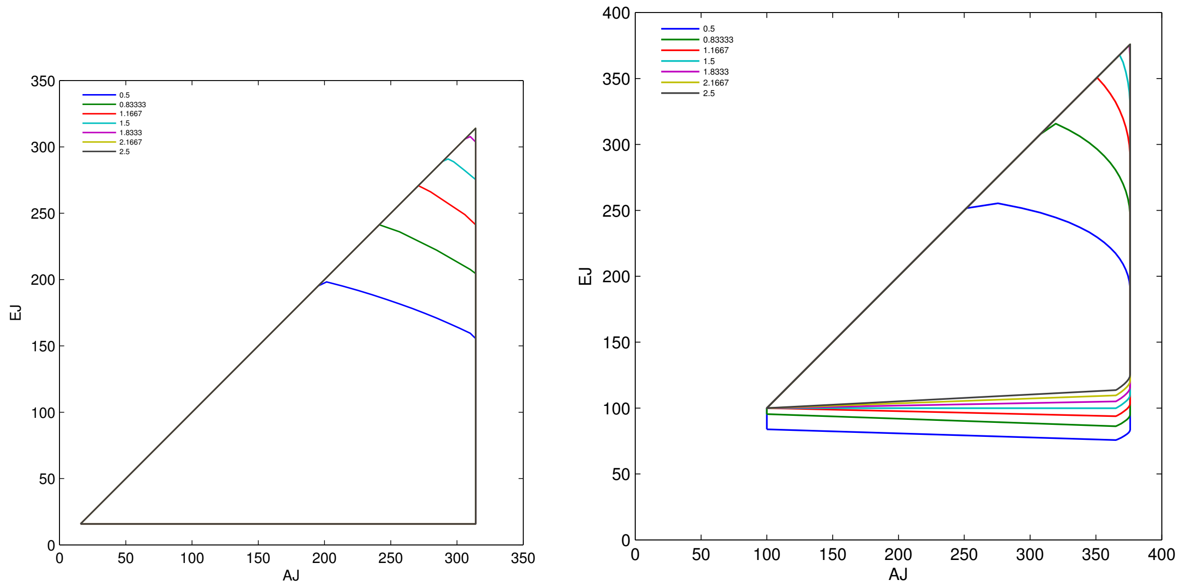



Figure 3: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the intrinsic resource growth factor, $\omega$, ranging from 0.5 to 2.5, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

Figure 7 shows the effect of variation in the relative importance of aggregate ecosystem services in utility, $\alpha$, with parameter values of $\alpha$ ranging from 0.1 to 0.9.

Figure 8 shows the effect of variation in the elasticity of substitution between consumption of the manufactured good and aggregate ecosystem-service consumption, $\sigma$, with parameter values of $\sigma$ ranging from 0.25 to 3.

Figure 9 shows the effect of variation in the relative importance of the consumptive ecosystem service in utility, $\beta$, with parameter values of $\beta$ ranging from 0.1 to 0.9.

Figure 10 shows the effect of variation in the elasticity of substitution between the consumptive and the non-consumptive ecosystem service, $\theta$, with parameter values of $\theta$ ranging from 0.25 to 3.

Figure 11 shows the effect of variation in the population growth factor, $n$, with parameter values of $n$ ranging from 0.5 to 2.5.

Figure 12 shows the effect of variation in the lower bound to intragenerational dis-

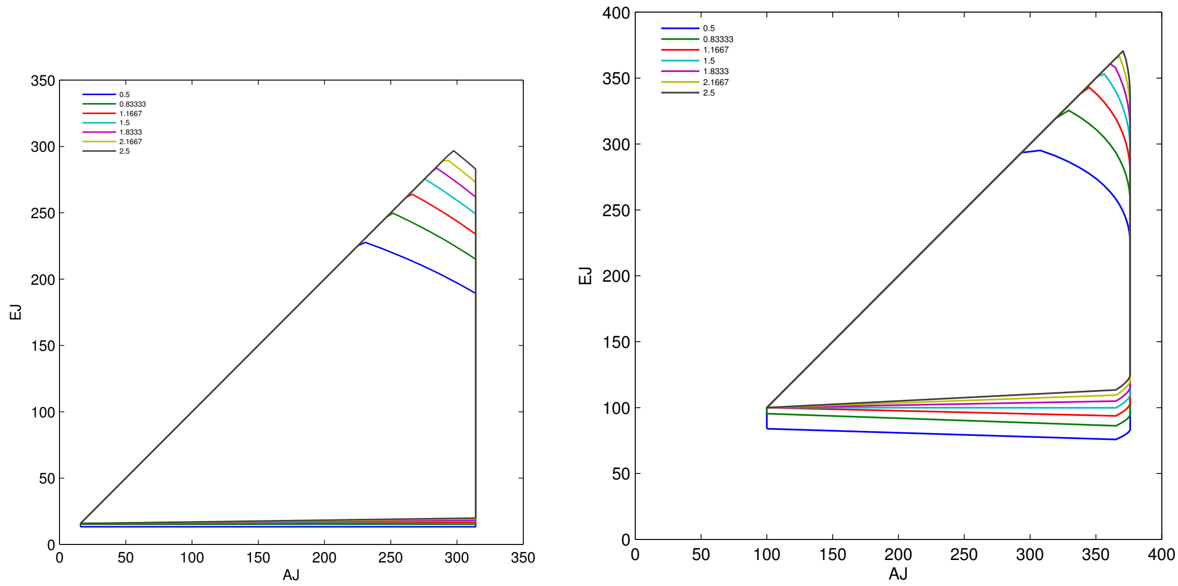



Figure 4: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the factor of technological progress in the resource harvesting sector, $\gamma$, ranging from 0.5 to 2.5, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

tribution, $\underline{\chi}$, with parameter values of $\underline{\chi}$ ranging from 0 to 25.

Figure 13 shows the effect of variation in the upper bound to intragenerational distribution, $\overline{\chi}$, with parameter values of $\overline{\chi}$ ranging from 0.1 to 1.1.

Figure 14 shows the effect of variation in the lower bound to intergenerational distribution, $\underline{\pi}$, with parameter values of $\underline{\pi}$ ranging from 550 to 792.

Figure 15 shows the effect of variation in the upper bound to intergenerational distribution, $\overline{\pi}$, with parameter values of $\overline{\pi}$ ranging from 100 to 800.

Figure 16 shows the effect of variation in the lower bound to second-generation consumptive-ecosystem-service consumption, $\underline{\xi}$, with parameter values of $\underline{\xi}$ ranging from 0 to 200.

Figure 17 shows the effect of variation in the upper bound to second-generation consumptive-ecosystem-service consumption, $\overline{\xi}$, with parameter values of $\overline{\xi}$ ranging from

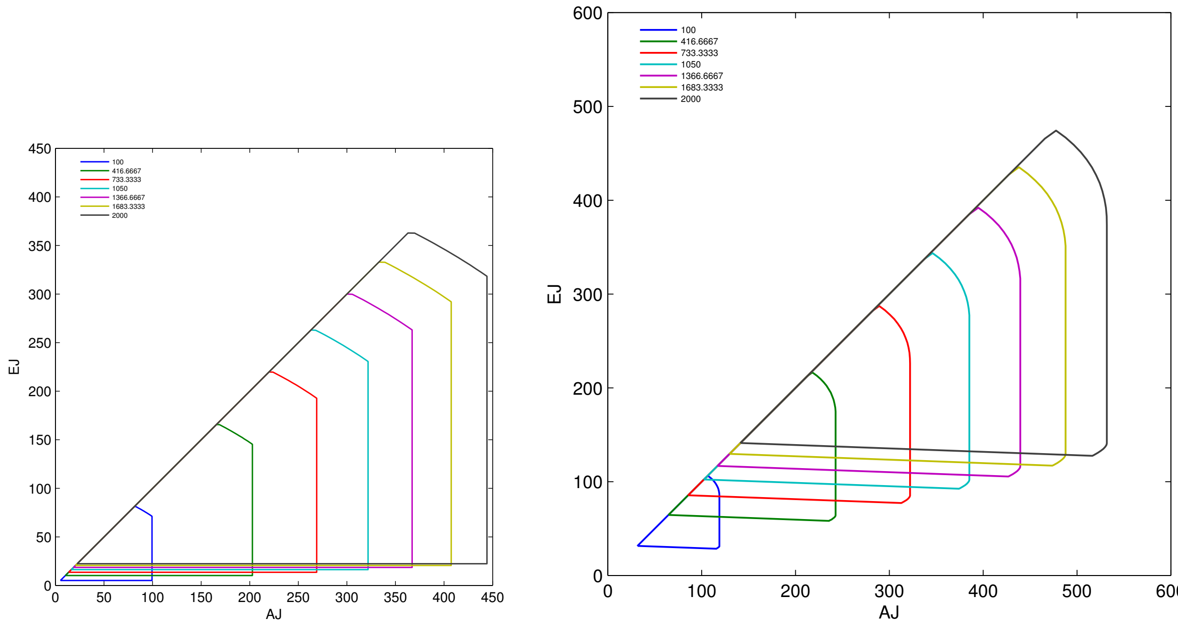



Figure 5: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the initial endowment with the manufactured good, $Y_1$, ranging from 100 to 2000, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

100 to 300.

# 5 Discussion and conclusion

In this paper, we developed an ecological-economic model that depicts the relationship between intragenerational and intergenerational justice in the use of ecosystem services against the backdrop of given societal circumstances. The model includes a differentiated description of ecosystem services (e.g. in terms of substitutability, excludability from use, consumptivity and rivalry in consumption) and certain *determinants* of the 'justice relationship'. Particularly, we distinguished two model variants: In model variant (a), the non-consumptive ecosystem service is a private good; in model variant (b),

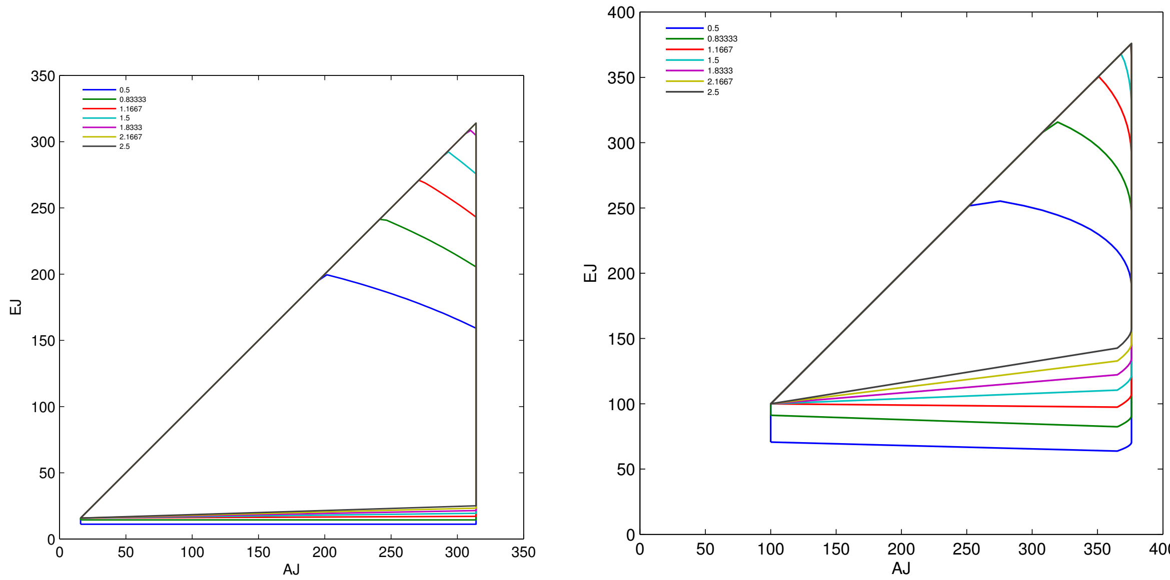



Figure 6: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the factor of technological progress in the manufacturing sector, $\mu$, ranging from 0.5 to 2.5, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

the non-consumptive ecosystem service is a pure public good. Further, we differentiated the determinants into an instrument of justice and several system determinants: The *instrument of justice* is the assignment of resource utilization rights to generation 1 and 2 by a social planner. The use of the *instrument of justice* decides on (*in*)*efficiency* – and, thereby, on the occurrence of rivalry, independency and facilitation in the 'justice relationship'. The *system determinants* set the context of a specific ecological-economic system and cannot be regulated by the social planner. The values of the *system determinants* decide on the *opportunity set* of feasible outcomes in terms of intragenerational and intergenerational environmental justice – and therewith on the shape of the *justice possibility frontier*.

The main contribution of this paper is the introduction of a generic ecological-economic model as a tool to systematically analyze the interdependencies between the

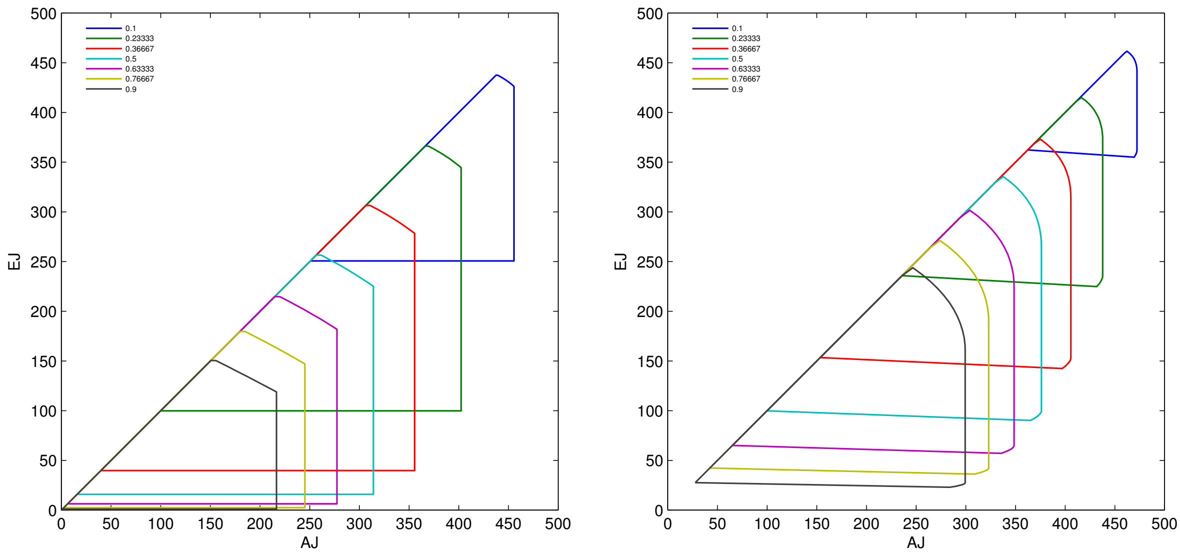



Figure 7: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the relative importance of aggregate ecosystem services in utility, $\alpha$, ranging from 0.1 to 0.9, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

objectives of intragenerational and intergenerational justice in ecosystem-service use. In future research, an *analytical model analysis* should be conducted to produce general model solutions - first, by analyzing how the use of the *instrument of justice* (i.e. the assignment of first- and second-generation resource utilization rights) impacts on the occurrence of rivalry, independency and facilitation in the 'justice relationship'; second, by analyzing how a change in one (or several) *system determinants* impacts on the shape of the justice possibility frontier - and, therewith, on the occurrence of rivalry, independency, facilitation in the 'justice relationship'. Using the method of numerical simulation, we illustrated possible findings regarding these two steps of model analysis. The numerical examples demonstrate that the introduced model is a valuable tool to explore political paths that consistently and effectively improve on both intragenerational and intergenerational environmental justice.

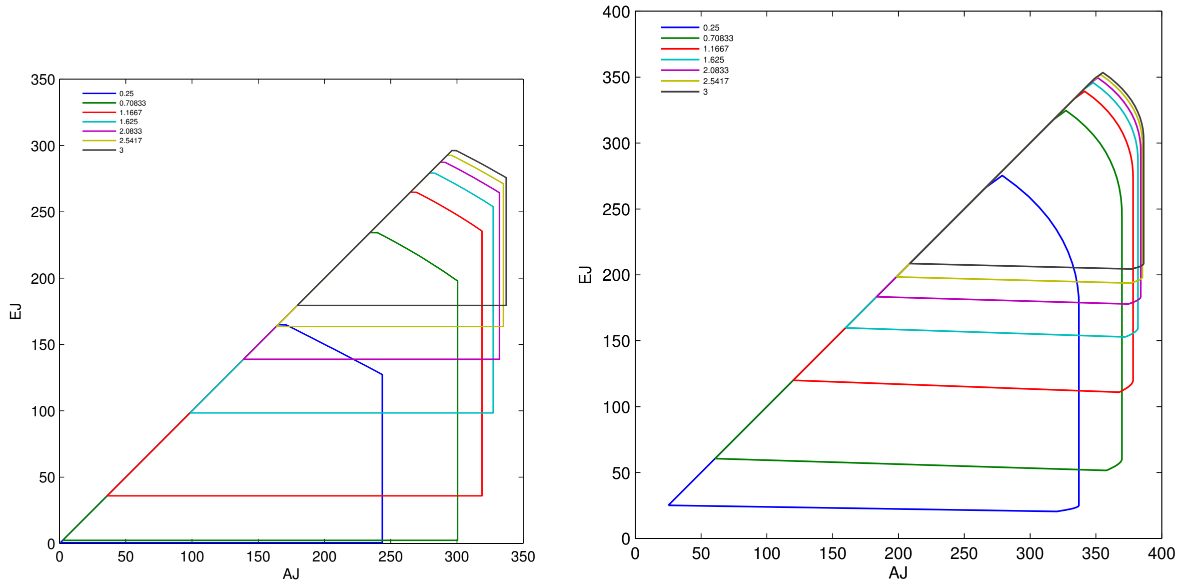



Figure 8: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the elasticity of substitution between consumption of the manufactured good and aggregate ecosystem-service consumption, $\sigma$, ranging from 0.25 to 3, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.


# Acknowledgments

We are grateful to Ralf Döring, Larry Karp, Max Stöven, Klara Stumpf, Rudi Voss and Hans-Peter Weikard for critical discussion, to Nikolai Huckle for conducting the numerical simulation and producing the graphs, and to the German Federal Ministry of Education and Research for financial support under grants 01UN1011A and 01110911E.

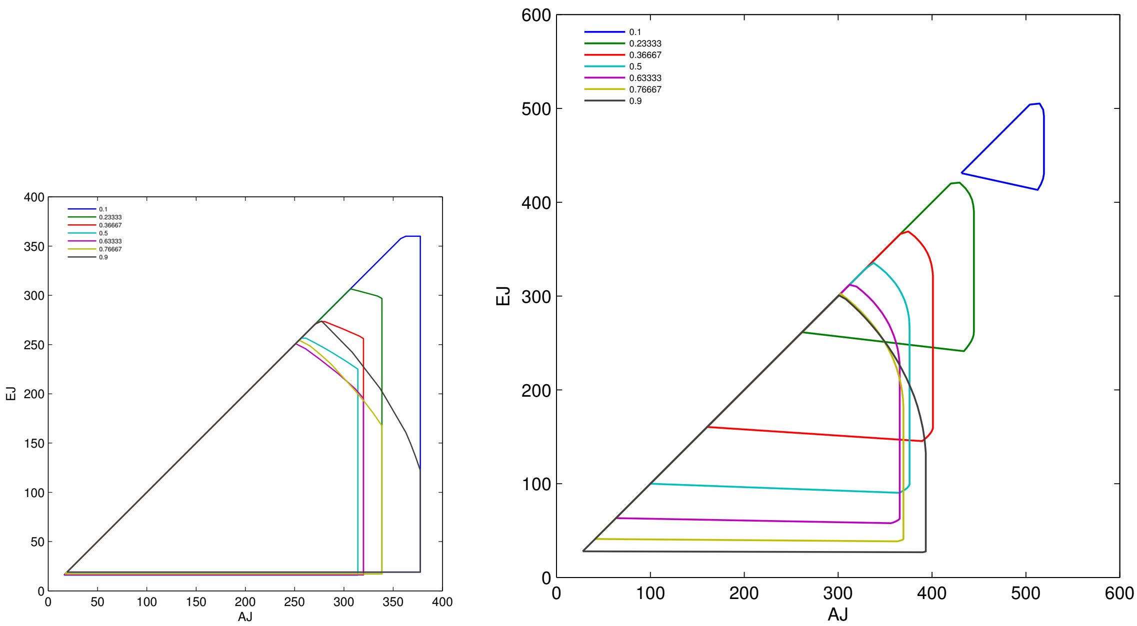



Figure 9: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the relative importance of the consumptive ecosystem service in utility, $\beta$, ranging from 0.1 to 0.9, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

# Appendix

## A.1 Analytical solution of model variant (a) (Section 4.1.1)

### Generation 1 ($i = A, B$)

The first-generation individual optimization problem (11) for $i = A, B$ can be solved by inserting constraints (1) and (5) for $\nu = 1$, $S^i = R^i - H^i$, into the utility function (10):

$$\max_{H^i} \left[ \left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left( \left(H^i\right)^{\frac{\theta-1}{\theta}} + \left(R^i - H^i\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \quad \text{s.t. (4)} \ . \tag{A.1}$$

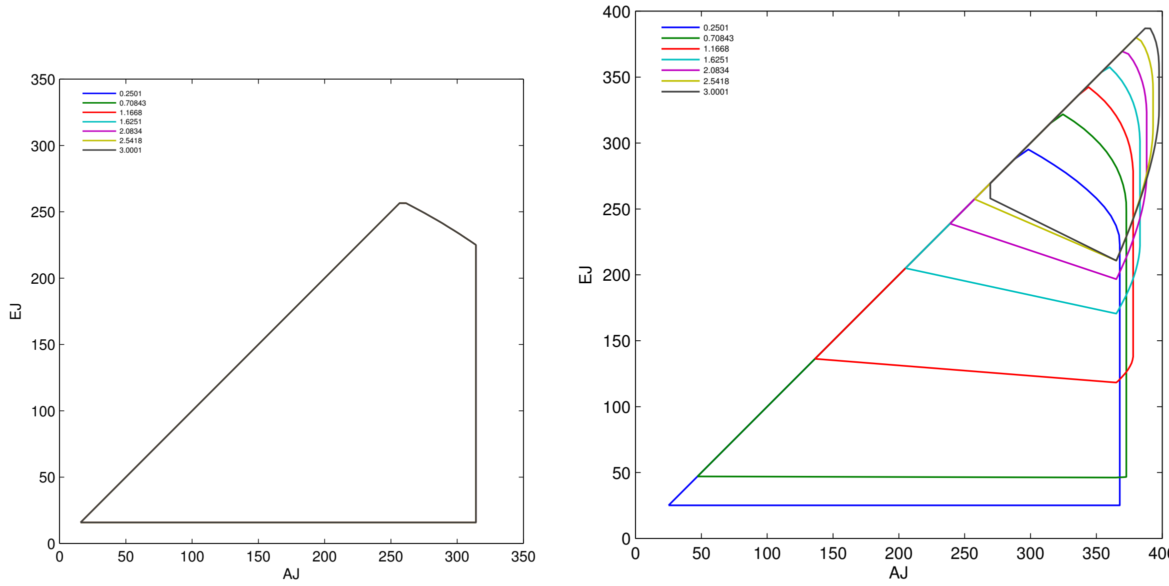



Figure 10: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the elasticity of substitution between the consumptive and the non-consumptive ecosystem service, $\theta$, ranging from 0.25 to 3, for model variant (a) ($\nu = 1$, top) and model variant (b) ($\nu = 0$, bottom). Other parameter values as in Figure 1.

The first-order condition for an interior solution is

$$\begin{aligned} 0 &= \left[ \left( \frac{Y_1}{2} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left(H^i\right)^{\frac{\theta-1}{\theta}} + \left(R^i - H^i\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}-1} \\ &\quad \times \left( \left(H^i\right)^{\frac{\theta-1}{\theta}} + \left(R^i - H^i\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}-1} \\ &\quad \times \left( \left(H^i\right)^{\frac{\theta-1}{\theta}-1} - \left(R^i - H^i\right)^{\frac{\theta-1}{\theta}-1} \right) . \end{aligned} \tag{A.2}$$

As the first two factors are not equal to zero for any value of $H^i$, the expression is zero if and only if the third factor is equal to zero:

$$\left(H^i\right)^{-\frac{1}{\theta}} = \left(R^i - H^i\right)^{-\frac{1}{\theta}} \tag{A.3}$$

$$H^i = R^i - H^i \tag{A.4}$$

$$H^i = \frac{R^i}{2} . \tag{A.5}$$

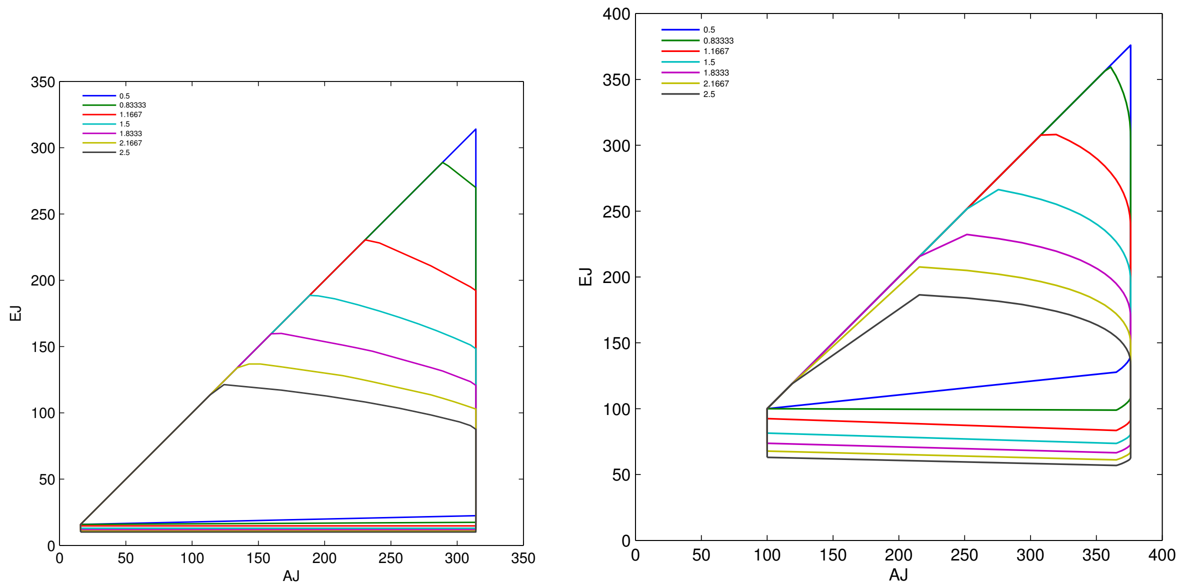



Figure 11: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the population growth factor, $n$, ranging from 0.5 to 2.5, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

This solution obviously satisfies constraint (4), that is, it is indeed an interior solution. Inserting (A.5) into constraint (5) for $\nu = 1$, $S^i = R^i - H^i$, yields

$$S^i = \frac{R^i}{2} \ . \tag{A.6}$$

Inserting (1), (A.5) and (A.6) into utility function (10) yields the indirect utility function

$$\begin{aligned} V^i &= \left[ \left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left( \left(\frac{R^i}{2}\right)^{\frac{\theta-1}{\theta}} + \left(\frac{R^i}{2}\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} && \text{(A.7)} \\ &= \left[ \left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left( 2^{\frac{\theta}{\theta-1}} \frac{R^i}{2} \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} && \text{(A.8)} \\ &= \left[ \left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left( 2^{\frac{1}{\theta-1}} R^i \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \ . && \text{(A.9)} \end{aligned}$$

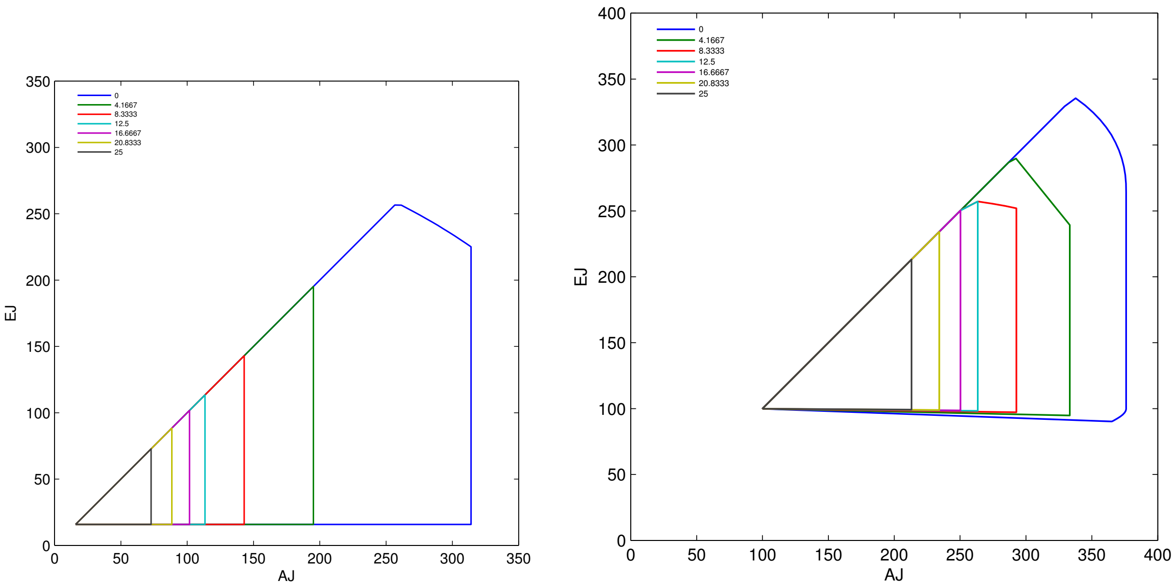
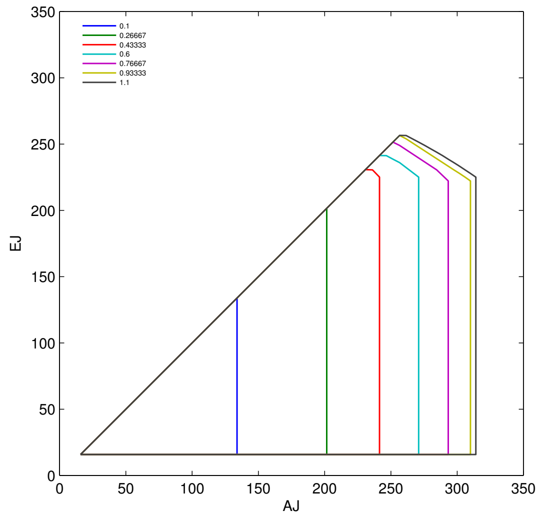



Figure 12: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the lower bound to intragenerational distribution, $\underline{\chi}$, ranging from 0 to 25, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

### Generation 2 ($\boldsymbol{i = C}$)

Likewise, the second-generation individual optimization problem (12) can be solved by inserting constraints (2) and (9) for $\nu = 1$, $S^C = R^C - H^C/\gamma$, into the utility function (10) for $i = C$:

$$\max_{H^C} \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( H^C \right)^{\frac{\theta-1}{\theta}} + \left( R^C - \frac{H^C}{\gamma} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \quad \text{s.t. (8)} \; . \qquad \text{(A.10)}$$



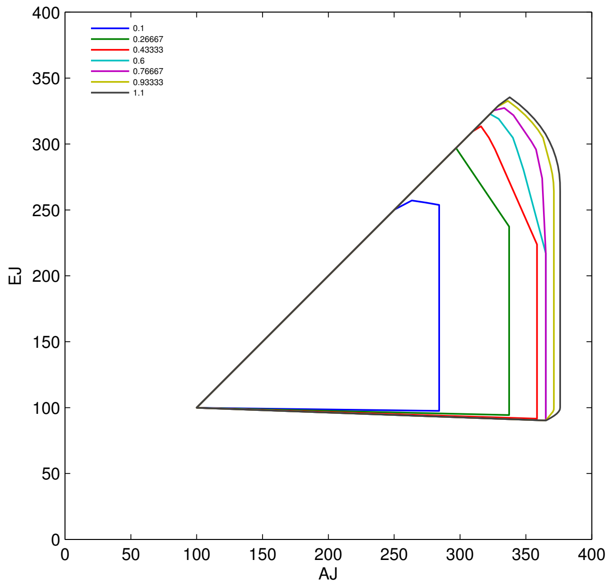




Figure 13: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the upper bound to intragenerational distribution, $\overline{\chi}$, ranging from 0.1 to 1.1, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

The first-order condition for an interior solution is

$$\begin{aligned} 0 &= \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left(H^C\right)^{\frac{\theta-1}{\theta}} + \left( R^C - \frac{H^C}{\gamma} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}-1} \\ &\times \left( \left(H^C\right)^{\frac{\theta-1}{\theta}} + \left( R^C - \frac{H^C}{\gamma} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}-1} \\ &\times \left( \left(H^C\right)^{\frac{\theta-1}{\theta}-1} - \frac{1}{\gamma} \left( R^C - \frac{H^C}{\gamma} \right)^{\frac{\theta-1}{\theta}-1} \right) . \end{aligned} \tag{A.11}$$

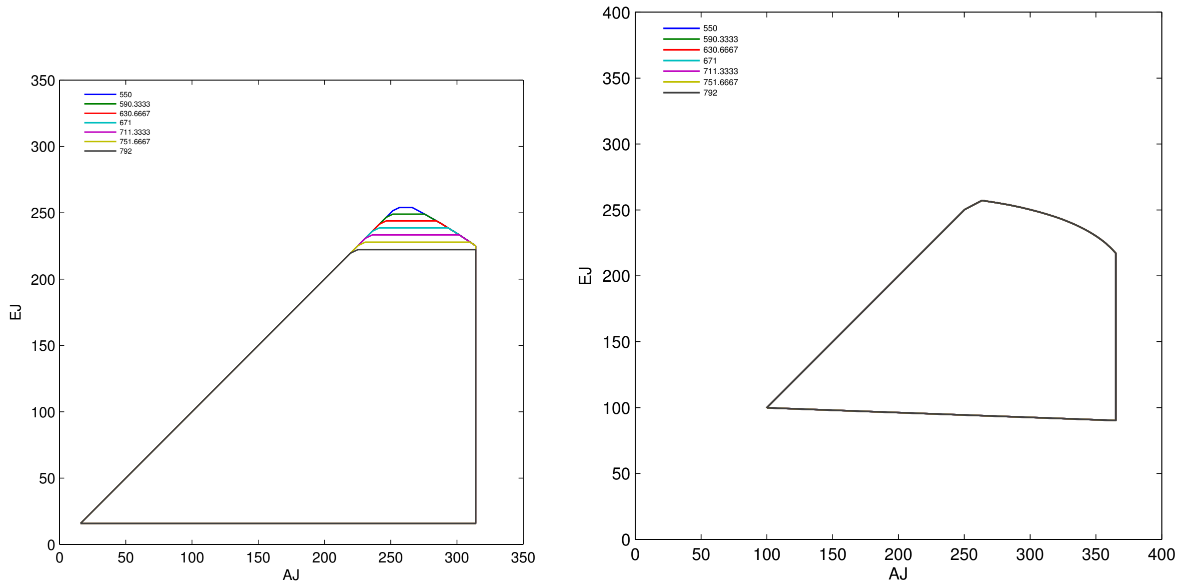



Figure 14: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the lower bound to intergenerational distribution, $\underline{\pi}$, ranging from 550 to 792, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

As the first two factors are not equal to zero for any value of $H^C$, the expression is zero if and only if the third factor is equal to zero:

$$\left(H^C\right)^{-\frac{1}{\theta}} = \frac{1}{\gamma}\left(R^C - \frac{H^C}{\gamma}\right)^{-\frac{1}{\theta}} \tag{A.12}$$

$$H^C = \gamma^{\theta}\left(R^C - \frac{H^C}{\gamma}\right) \tag{A.13}$$

$$H^C = \frac{\gamma^{\theta}}{1+\gamma^{\theta-1}}R^C = \frac{R^C}{\gamma^{-\theta}+\gamma^{-1}} \; . \tag{A.14}$$

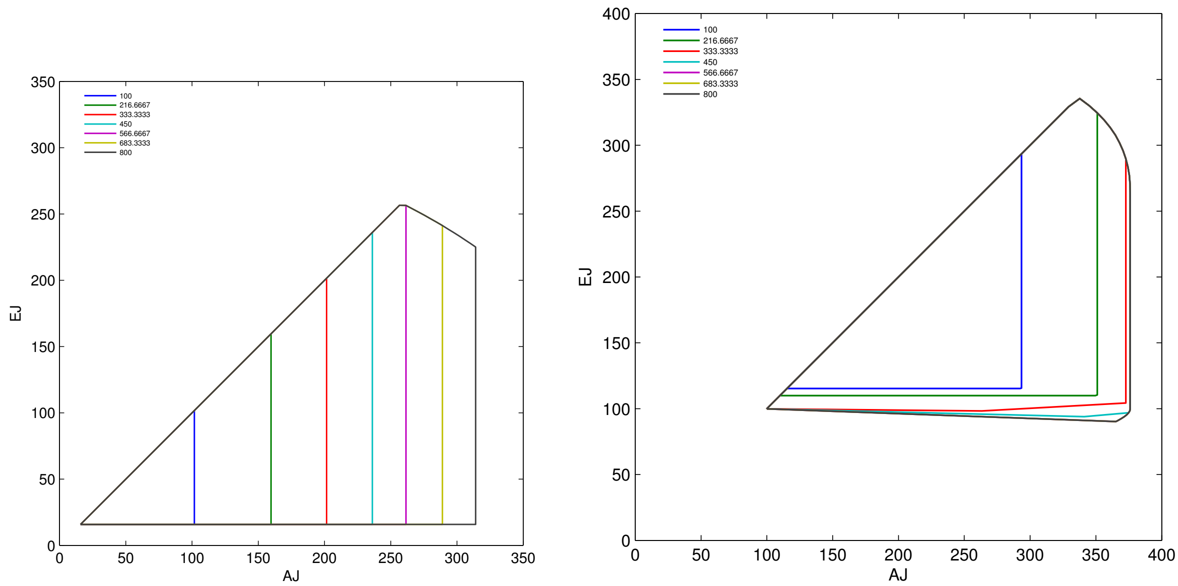



Figure 15: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the upper bound to intergenerational distribution, $\overline{\pi}$, ranging from 100 to 800, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

As $1/(\gamma^{-\theta}+\gamma^{-1}) < \gamma$, this solution satisfies constraint (8), that is, it is indeed an interior solution. Inserting (A.14) into constraint (9) for $\nu = 1$, $S^C = R^C - H^C/\gamma$, yields

$$S^C = R^C - \frac{1}{\gamma}\frac{\gamma^\theta}{1+\gamma^{\theta-1}}R^C \tag{A.15}$$

$$= \left(1 - \frac{\gamma^{\theta-1}}{1+\gamma^{\theta-1}}\right)R^C \tag{A.16}$$

$$= \frac{R^C}{1+\gamma^{\theta-1}} \tag{A.17}$$

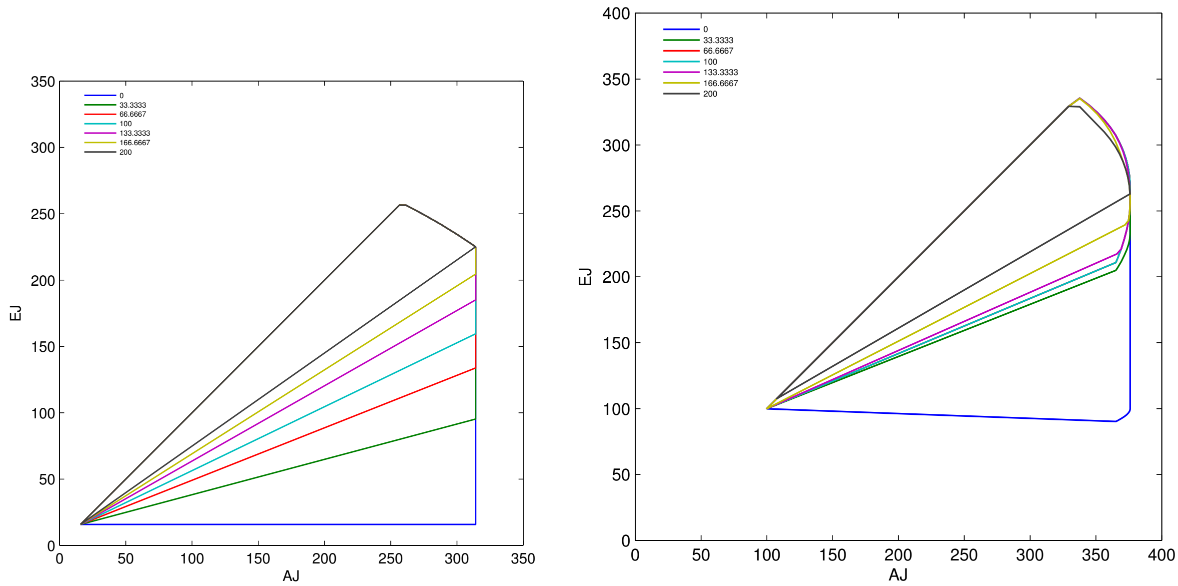



Figure 16: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the lower bound to second-generation consumptive-ecosystem-service consumption, $\underline{\xi}$, ranging from 0 to 200, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

Inserting (2), (A.14) and (A.17) into utility function (10) yields the indirect utility function

$$V^C = \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( \frac{R^C}{\gamma^{-\theta} + \gamma^{-1}} \right)^{\frac{\theta-1}{\theta}} + \left( \frac{R^C}{1 + \gamma^{\theta-1}} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1} \frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{A.18}$$

$$= \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( \left( \frac{1}{\gamma^{-\theta} + \gamma^{-1}} \right)^{\frac{\theta-1}{\theta}} + \left( \frac{1}{1 + \gamma^{\theta-1}} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} R^C \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{A.19}$$

$$= \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left(1 + \gamma^{\theta-1}\right)^{\frac{1}{\theta-1}} R^C \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} . \tag{A.20}$$

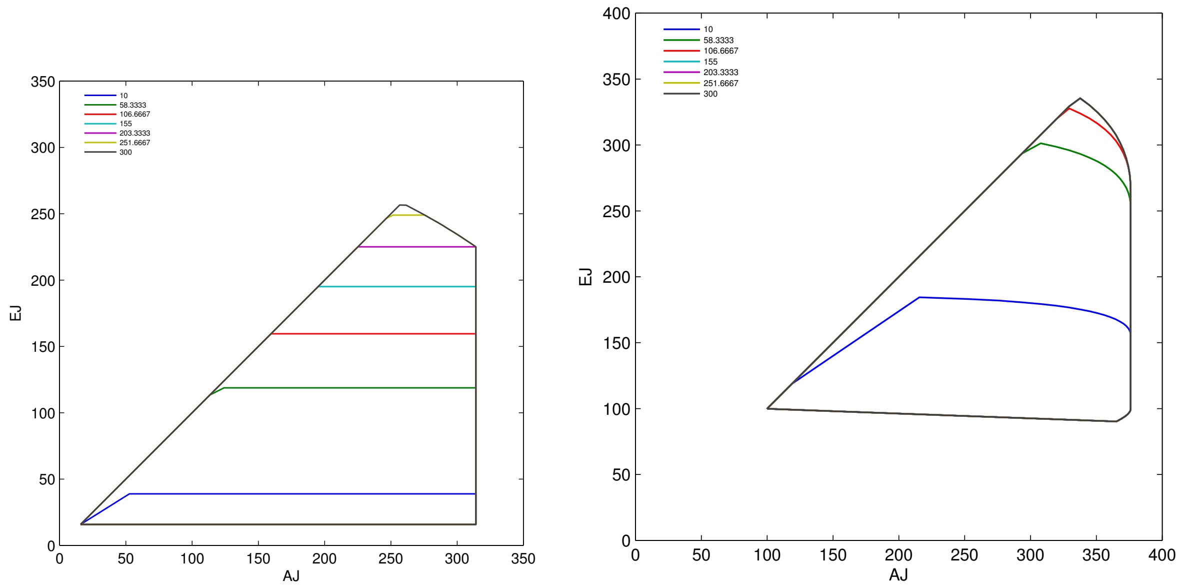



Figure 17: Justice possibility set in terms of intragenerational environmental justice (AJ) and intergenerational environmental justice (EJ) for different values of the upper bound to second-generation consumptive-ecosystem-service consumption, $\bar{\xi}$, ranging from 100 to 300, for model variant (a) ($\nu = 1$, left) and model variant (b) ($\nu = 0$, right). Other parameter values as in Figure 1.

## A.2 Analytical solution of model variant (b) (Section 4.1.2)

### Generation 1 ($i = A, B$)

The first-generation individual optimization problem (11) for $i = A, B$ can be solved by inserting constraints (1) and (5) for $\nu = 0$, $S^i = R_1 - H^i - H^j$ ($j = A, B$ and $j \neq i$), into the utility function (10):

$$\max_{H^i} \left[ \left( \frac{Y_1}{2} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( H^i \right)^{\frac{\theta-1}{\theta}} + \left( R_1 - H^i - H^j \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \quad \text{s.t. (4)} . \tag{A.21}$$

The first-order condition for an interior solution is

$$
\begin{aligned}
0 \;=\; & \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(\left(H^i\right)^{\frac{\theta-1}{\theta}} + \left(R_1 - H^i - H^j\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}-1} \\
& \times \left(\left(H^i\right)^{\frac{\theta-1}{\theta}} + \left(R_1 - H^i - H^j\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}-1} \\
& \times \left(\left(H^i\right)^{\frac{\theta-1}{\theta}-1} - \left(R_1 - H^i - H^j\right)^{\frac{\theta-1}{\theta}-1}\right) \; . \qquad \text{(A.22)}
\end{aligned}
$$

As the first two factors are not equal to zero for any value of $H^i$, the expression is zero if and only if the third factor is equal to zero:

$$
\begin{aligned}
\left(H^i\right)^{-\frac{1}{\theta}} &= \left(R_1 - H^i - H^j\right)^{-\frac{1}{\theta}} && \text{(A.23)} \\
H^i &= R_1 - H^i - H^j && \text{(A.24)} \\
H^i &= \frac{1}{2}\left(R_1 - H^j\right) \; . && \text{(A.25)}
\end{aligned}
$$

This reaction function specifies individual $i$'s optimal choice of $H^i$ given individual $j$'s choice of $H^j$. As optimization problem (A.21) is strictly concave in $H^i$, any value of $H^i$ smaller (greater) than the one given by (A.25) implies that individual $i$ could improve his own utility by choosing a larger (smaller) value of $H^i$. Likewise, one obtains individual $j$'s reaction function as

$$
H^j = \frac{1}{2}\left(R_1 - H^i\right) \; , \qquad \text{(A.26)}
$$

which has analogous stability properties as $H^i$ (A.25) and which can be rearranged into

$$
H^i = R_1 - 2H^j \; . \qquad \text{(A.27)}
$$

With the reaction functions (A.25) and (A.26) of individuals $i$ and $j$ ($i = A, B$, $i \neq j$), a unique and stable Nash equilibrium exists as follows (Figure 18).

**Case 1-I.** Equating (A.25) and (A.27) yields

$$
\begin{aligned}
\frac{1}{2}\left(R_1 - H^j\right) &= R_1 - 2H^j && \text{(A.28)} \\
H^j &= \frac{R_1}{3} && \text{(A.29)}
\end{aligned}
$$

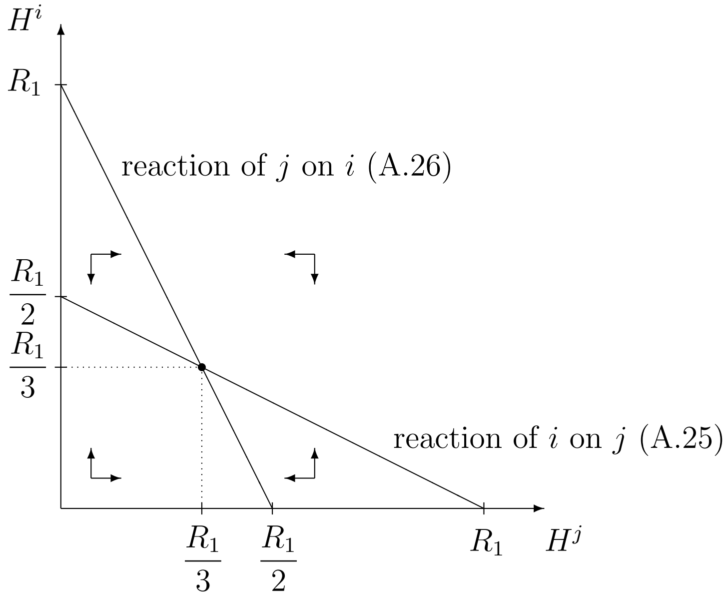



Figure 18: Reaction functions (A.25) and (A.26) of individuals $i$ and $j$ (for $i, j = A, B$ and $j \neq i$). Their intersection, marked by a dot, is the (unique and stable) symmetric Nash equilibrium (A.29), (A.30) (case 1-I). Arrows indicate transitional dynamics towards the equilibrium.

and, inserting (A.29) into (A.25)

$$H^i = \frac{R_1}{3} \ . \tag{A.30}$$

This symmetric solution, (A.29) and (A.30), holds if it is attainable with the resource utilization rights $R^i$ and $R^j$ assigned to individuals $i$ and $j$ (Constraint 4), i.e. for $R^i \geq R_1/3$ and $R^j \geq R_1/3$. In this case, inserting (A.29) and (A.30) into (5) for $\nu = 0$, $S^i = R_1 - H^i - H^j$, yields

$$S^i = \frac{R_1}{3} \quad \text{for } i = A, B \ . \tag{A.31}$$

Inserting (1), (A.30) and (A.31) into utility function (10) yields the indirect utility function

$$V^i = \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(\left(\frac{R_1}{3}\right)^{\frac{\theta-1}{\theta}} + \left(\frac{R_1}{3}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{A.32}$$

$$= \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{2^{\frac{\theta}{\theta-1}}}{3}R_1\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} . \tag{A.33}$$

Inserting (A.29) and (A.30) into (6) yields the resource stock available to generation 2:

$$R_2 = \omega\left(R_1 - \frac{R_1}{3} - \frac{R_1}{3}\right) = \frac{\omega}{3}R_1 . \tag{A.34}$$

**Case 1-II.** For $R^i < R_1/3$ (with $i = A, B$), i.e. if in the optimal solution resource utilization rights $R^i$ are a binding constraint (due to 4) for both individuals $i$ and $j$, the solution (A.29), (A.30) is not attainable. In this case, as optimization problem (A.21) is strictly concave in $H^i$, both individuals will choose a corner solution for $H^i$, namely the largest value of $H^i$ attainable within constraint (4):

$$H^i = R^i \quad \text{for } i = A, B . \tag{A.35}$$

Inserting (A.35) into (5) for $\nu = 0$, $S^i = R_1 - H^i - H^j$, yields

$$S^i = R_1 - R^i - R^j \quad \text{for } i, j = A, B,\ j \neq i . \tag{A.36}$$

Inserting (1), (A.35) and (A.36) into utility function (10) yields the indirect utility function (for $i, j = A, B$, $j \neq i$)

$$V^i = \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(R^{i\,\frac{\theta-1}{\theta}} + \left(R_1 - R^i - R^j\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} . \tag{A.37}$$

Inserting (A.35) into (6) yields the resource stock available to generation 2:

$$R_2 = \omega\left(R_1 - R^A - R^B\right) . \tag{A.38}$$

**Case 1-III.** For an asymmetric assignment of resource utilization rights of $R^i \geq R_1/3$ and $R^j < R_1/3$ (with $i, j = A, B$ and $j \neq i$), i.e. if in the optimal solution resource utilization rights are a binding constraint for individual $j$ but not for individual $i$, the constrained individual $j$ will choose, as optimization problem (A.21) is strictly concave in $H^j$, a corner solution for $H^j$, namely the largest value of $H^j$ attainable within constraint (4):

$$H^j = R^j \ . \tag{A.39}$$

As an optimal reaction based on the reaction function (A.25), individual $i$ will then choose

$$H^i = \frac{1}{2}\left(R_1 - H^j\right) = \frac{1}{2}\left(R_1 - R^j\right) \ . \tag{A.40}$$

Inserting (A.39) and (A.40) into (5) for $\nu = 0$, $S^i = R_1 - H^i - H^j$, yields (for $i, j = A, B$, $j \neq i$)

$$S^i = S^j = R_1 - \frac{1}{2}\left(R_1 - R^j\right) - R^j = \frac{1}{2}\left(R_1 - R^j\right) \ . \tag{A.41}$$

Inserting (1), (A.39), (A.40) and (A.41) into utility function (10) yields the indirect utility functions (for $i, j = A, B$, $j \neq i$):

$$V^i = \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(\left(\frac{R_1 - R^j}{2}\right)^{\frac{\theta-1}{\theta}} + \left(\frac{R_1 - R^j}{2}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{A.42}$$

$$= \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(2^{\frac{\theta}{\theta-1}}\frac{R_1 - R^j}{2}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{A.43}$$

$$= \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left(2^{\frac{1}{\theta-1}}\left(R_1 - R^j\right)\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \ . \tag{A.44}$$

and

$$V^j = \left[\left(\frac{Y_1}{2}\right)^{\frac{\sigma-1}{\sigma}} + \left({R^j}^{\frac{\theta-1}{\theta}} + \left(\frac{R_1 - R^j}{2}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \ . \tag{A.45}$$

Inserting (A.39) and (A.40) into (6) yields the resource stock available to generation 2:

$$R_2 = \omega\left(R_1 - \frac{1}{2}\left(R_1 - R^j\right) - R^j\right) = \frac{\omega}{2}\left(R_1 - R^j\right) \ . \tag{A.46}$$

**Generation 2 ($i = C$)**

To analyze the strategic interaction in the second-generation individual optimization problems (12) among the $2n$ individuals $C$, one needs to distinguish between some individual $C$ proper and some other representative individual $\bar{C}$, which also belongs to the second generation but is different from $C$. Depending on the harvesting decisions $H^C$ of individual $C$ and $H^{\bar{C}}$ of all other $2n-1$ individuals $\bar{C}$, the amount of the non-consumptive public ecosystem service, according to (9) for $\nu = 0$, is given by

$$S^C = S^{\bar{C}} = R^C - \frac{H^C}{\gamma} + \left[R_2 - R^C - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right] \tag{A.47}$$

$$= R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma} \ . \tag{A.48}$$

Individual $C$'s optimization problem (12), given the action $H^{\bar{C}}$ of individual $\bar{C}$, can be solved by inserting constraints (2) and (A.48) into the utility function (10) for $i = C$:

$$\max_{H^C} \quad \left[\left(\frac{\mu Y_1}{2n}\right)^{\frac{\sigma-1}{\sigma}} + \left(\left(H^C\right)^{\frac{\theta-1}{\theta}} + \left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$
$$\text{s.t. (8)} \ . \tag{A.49}$$

The first-order condition for an interior solution is

$$\begin{aligned}
0 \;=\; & \left[\left(\frac{\mu Y_1}{2n}\right)^{\frac{\sigma-1}{\sigma}} + \left(\left(H^C\right)^{\frac{\theta-1}{\theta}} + \left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}-1} \\
& \times \left(\left(H^C\right)^{\frac{\theta-1}{\theta}} + \left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}-1} \\
& \times \left(\left(H^C\right)^{\frac{\theta-1}{\theta}-1} - \frac{1}{\gamma}\left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right)^{\frac{\theta-1}{\theta}-1}\right) \ .
\end{aligned} \tag{A.50}$$

As the first two factors are not equal to zero for any value of $H^C$, the expression is zero if and only if the third factor is equal to zero:

$$\left(H^C\right)^{-\frac{1}{\theta}} = \frac{1}{\gamma}\left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right)^{-\frac{1}{\theta}} \quad \text{(A.51)}$$

$$H^C = \gamma^\theta \left(R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right) \quad \text{(A.52)}$$

$$H^C = \frac{\gamma^\theta}{1+\gamma^{\theta-1}}\left(R_2 - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right) \quad \text{(A.53)}$$

$$= \frac{1}{\gamma^{-\theta}+\gamma^{-1}}\left(R_2 - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right) . \quad \text{(A.54)}$$

This reaction function specifies individual $C$'s optimal choice of $H^C$ given the other $2n-1$ individuals' $\bar{C}$ choice of $H^{\bar{C}}$. As optimization problem (A.49) is strictly concave in $H^C$, any value of $H^C$ smaller (greater) than the one given by (A.54) implies that individual $C$ could improve his own utility by choosing a larger (smaller) value of $H^C$. Likewise, one obtains the $2n-1$ individuals' $\bar{C}$ reaction function as

$$H^{\bar{C}} = \frac{1}{\gamma^{-\theta}+\gamma^{-1}}\left(R_2 - (2n-1)\frac{H^C}{\gamma}\right) , \quad \text{(A.55)}$$

which has analogous stability properties as $H^C$ (A.54) and which can be rearranged into

$$H^C = \frac{\gamma}{2n-1}\left(R_2 - (\gamma^{-\theta}+\gamma^{-1})H^{\bar{C}}\right) . \quad \text{(A.56)}$$

With the reaction functions (A.54) and (A.55) of individuals $C$ and $\bar{C}$, a unique and stable Nash equilibrium exists as follows.

**Case 2-I.** Equating (A.54) and (A.56) yields

$$\frac{1}{\gamma^{-\theta}+\gamma^{-1}}\left(R_2 - (2n-1)\frac{H^{\bar{C}}}{\gamma}\right) = \frac{\gamma}{2n-1}\left(R_2 - (\gamma^{-\theta}+\gamma^{-1})H^{\bar{C}}\right) \quad \text{(A.57)}$$

$$H^{\bar{C}} = \frac{R_2}{\gamma^{-\theta}+2n\gamma^{-1}} \quad \text{(A.58)}$$

and, inserting (A.58) into (A.54)

$$H^C = \frac{R_2}{\gamma^{-\theta}+2n\gamma^{-1}} . \quad \text{(A.59)}$$

This solution holds if it is attainable with the resource utilization rights $R^C$ assigned to individuals $C$ (Constraint 8), i.e. for

$$R^C \geq \frac{H^C}{\gamma} = \frac{R_2}{\gamma^{1-\theta} + 2n} \ . \tag{A.60}$$

In this case, inserting (A.58) and (A.59) into (A.48) yields

$$\begin{aligned} S^C &= R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma} && \text{(A.61)} \\ &= R_2 - \frac{R_2}{\gamma^{1-\theta} + 2n} - (2n-1)\frac{R_2}{\gamma^{1-\theta} + 2n} && \text{(A.62)} \\ &= \frac{R_2}{1 + 2n\gamma^{\theta-1}} \ . && \text{(A.63)} \end{aligned}$$

Inserting (2), (A.59) and (A.63) into utility function (10) for $i = C$ yields the indirect utility function

$$\begin{aligned} V^C &= \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( \frac{R_2}{\gamma^{-\theta} + 2n\gamma^{-1}} \right)^{\frac{\theta-1}{\theta}} + \left( \frac{R_2}{1 + 2n\gamma^{\theta-1}} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} && \text{(A.64)} \\ &= \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \frac{\left(1 + \gamma^{\theta-1}\right)^{\frac{\theta}{\theta-1}}}{1 + 2n\gamma^{\theta-1}} R_2 \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \ . && \text{(A.65)} \end{aligned}$$

**Case 2-II.** For $R^C < R_2/(\gamma^{1-\theta} + 2n)$, i.e. if in the optimal solution resource utilization rights $R^C$ are a binding constraint (due to 8), the solution (A.59) is not attainable. In this case, as optimization problem (A.49) is strictly concave in $H^C$, individuals $C$ will chose a corner solution for $H^C$, namely the largest value of $H^C$ attainable within constraint (8):

$$H^C = \gamma R^C \ . \tag{A.66}$$

Inserting (A.66) into (A.48) for yields

$$\begin{aligned} S^C &= R_2 - \frac{H^C}{\gamma} - (2n-1)\frac{H^{\bar{C}}}{\gamma} && \text{(A.67)} \\ &= R_2 - R^C - (2n-1)R^C && \text{(A.68)} \\ &= R_2 - 2nR^C \ . && \text{(A.69)} \end{aligned}$$

Inserting (2), (A.66) and (A.69) into utility function (10) for $i = C$ yields the indirect utility function

$$V^C = \left[ \left( \frac{\mu Y_1}{2n} \right)^{\frac{\sigma-1}{\sigma}} + \left( \left( \gamma R^C \right)^{\frac{\theta-1}{\theta}} + \left( R_2 - 2nR^C \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} . \quad \text{(A.70)}$$

## A.3 Comparative statics of solution for model variant (a) (Section 4.2)

available from the authors upon request

## A.4 Comparative statics of solution for model variant (b) (Section 4.2)

available from the authors upon request

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