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Responsibility, inequality, efficiency, and equity in four sustainability paradigms: insights for the global environment from a cross-development analytical model

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Abstract This paper develops a theoretical framework to assess the feasibility of global environmental sustainability solutions based on one or more value changes. The framework represents four sustainability paradigms (weak sustainability WS, a-growth AG, de-growth DG, strong sustainability SS) and five value changes (i.e. a sense of responsibility for nature, future generations, or the current generation in developing countries; aversion to inequality for the current generation or future generations). It defines solutions in terms of consumption, environment use, and welfare for representative individuals in both developed (OECD) and developing (non-OECD) countries. Solutions are characterised by efficiency (i.e. Pareto and Kaldor–Hicks) with respect to welfare and by intra- and inter-generational equality for consumption, environment use, and welfare, by confirming internal consistency and consistency with alternative equity approaches for utilitarianism (i.e. Harsanyi), egalitarianism (i.e. Arneson for welfare; Dworkin for consumption or environment use; Sen for consumption and environment use), and contractarianism (i.e. Rawls). Theoretical and operational insights are described for alternative sustainability paradigms and equity approaches. In terms of feasibility based on improved technology, decreased population, and modified consumption, the ordering is responsibility for future generations > responsibility for the current generation in developing countries > aversion to inequality for the current generation > aversion to inequality for future generations and AG > SS > DG > WS: responsibility for nature is unfeasible. In terms of internal consistency, responsibility for future generations > responsibility for the current generation in developing countries = aversion to inequality for the current generation = aversion to inequality for future generations and SS > AG > DG; WS is internally inconsistent. In terms of consistency with an equity approach, responsibility for future generations > responsibility

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for the current generation in developing countries = aversion to inequality for future generations > aversion to inequality for the current generation and SS > AG > DG > WS.

Keywords Weak sustainability · A-growth · De-growth · Strong sustainability · Duty · Inequality · Efficiency · Equity

1 Introduction

Four main sustainability paradigms have been suggested in the literature (Zagonari 2016): weak sustainability, a-growth, de-growth, and strong sustainability. Note that in this context, the economic general equilibrium framework is similar to weak sustainability, whereas the ecosystem services framework is close to strong sustainability.

Two main value changes have been evoked to achieve sustainability: a sense of responsibility, whether this is for nature (Pedersen 2015; Saniotis 2012; Van der Werff et al. 2013) or for current and future generations (Caselles 2013; Koukouzelis 2012); and an aversion to inequality, whether this is with respect to current or future generations (Golub et al. 2013; Kopnina 2016). Note that improved environmental technology, a decreased world population, and modified consumption patterns can be considered here as context changes for any combination of paradigms and values.

The purpose of this paper is to develop a model for the four sustainability paradigms within a single framework that accounts for changes in five values (a sense of responsibility for nature, for the current generation, or for future generations; an aversion to intra- or inter-generational inequality). The goal is to assess the feasibility of global environmental sustainability solutions that depend on changes in one or more of these values. In particular, I will characterise analytical and numerical solutions for cases based on extreme and estimated parameter values using data on the consumption level, the direct and indirect use of Earth's environmental resources (hereafter, *environment use*), and the welfare level for representative individuals in both developed countries (i.e. the 35 OECD countries) and developing countries (i.e. the non-OECD countries). This will rank solutions in terms of feasibility classes: a reduction in welfare by > 25%, by 12.5–25%, and by < 12.5% will be considered unfeasible, slightly feasible, and moderately feasible, respectively, whereas an increase in welfare will be considered feasible.

Moreover, these characterisations will let us identify efficient solutions (i.e. Pareto and Kaldor–Hicks efficiency with respect to welfare) and measure equality (i.e. inequalities with respect to consumption, environment use, and welfare) at both intra- and inter-generational levels. This will reveal the internal consistency of the solutions with the assumptions of the four sustainability paradigms with respect to equality (e.g. weak sustainability cannot be linked to a large aversion to inequality) and efficiency (e.g. weak sustainability must be coupled with Kaldor–Hicks efficiency).

Finally, these calculations will identify which sustainability solution is consistent with a utilitarian approach (i.e. Harsanyi), an egalitarian approach (i.e. Arneson for welfare; Dworkin for consumption or environment use; Sen for consumption and environment use), or a contractarian approach (i.e. Rawls) (Habib 2013). This will characterise the sustainability solutions in terms of distributive justice (hereafter, *equity*).

In other words, this study can be read from a normative perspective so that, for a given sustainability paradigm or approach to equity, the framework defines which global environmental sustainability conditions should be achieved, if any. Alternatively, this study can be read from a positive perspective so that, for any sustainability paradigm or approach to equity, it identifies which value changes (i.e. demand policies vs. production policies such as taxes and standards) are crucial to meet sustainability conditions.

Note that all insights about feasible sustainability for the current generation are based on per capita data for representative individuals in OECD and non-OECD countries, weighted according to the country's proportion of the world's population. Moreover, sustainability conditions are checked for the main context changes (i.e. improved technology, decreased population, and modified consumption). Finally, a current, globally representative individual is compared with a future globally representative individual to describe inter-generational equity and efficiency, without splitting future generations into OECD and non-OECD countries.

This study provides several novel contributions to our knowledge. First, this study characterises the main sustainability paradigms (i.e. weak sustainability, a-growth, de-growth, strong sustainability) in terms of a few essential features (i.e. efficiency, equity, and consistency) and formalises these paradigms as constrained maximisation or minimisation problems using a few quantitative variables (e.g. GDP and ecological footprint). This allows comparison and ranking of the sustainability paradigms in terms of their feasibility, efficiency, equity, and internal consistency. Note that these sustainability paradigms represent continuity (weak sustainability and strong sustainability) and minimisation of environmental and social impacts (a-growth and de-growth) as typical aspects of sustainability, which Salas-Zapata et al. (2017) defined as "social and ecological resilience". In particular, my analysis shows how some sustainability paradigms might be unfeasible in certain contexts (e.g. a-growth is unfeasible without improved technology) or how they require specific contexts to be feasible (e.g. de-growth can be feasible if combined with modified consumption, improved technology, or a reduced population).

Second, this study is the first to integrate the main value changes evoked to achieve sustainability (i.e. responsibility for nature, responsibility for future and current generations, and aversion to inter and intra-generational inequality) in a single framework. This allows a comparison and ranking of value changes in terms of their feasibility. Note that these values can be defined as "secular principles", with "religious precepts" sometimes considered in addition to secular principles (e.g. the dignity of non-humans and harmony with nature in Hinduism or Buddhism, stewardship in Judaism, trusteeship and parsimony in Islam, love of neighbours in Christianity). Such religious precepts are sometimes similar to secular principles (e.g. responsibility for nature in Hinduism or Buddhism, responsibility for future generations in Judaism and Islam, responsibility for the current generation in Christianity). Alternatively, secular principles are sometimes considered in addition to religious precepts, as in the cases of efficiency or aversion to inequality.

Third, this study is the first to relate sustainability paradigms to the value changes required to achieve global sustainability. This will reveal feasible couples of sustainability paradigms with value changes that meet equity and efficiency criteria, feasible couples that satisfy the internal consistency criterion, and feasible couples that do not meet any criterion. In other words, this study contributes to the discussion of the most evident value changes required to achieve global sustainability by considering feasibility, efficiency, and equity. It accomplishes this goal by linking the value changes to the most common sustainability paradigms within a single framework that also depicts essential features such as modified consumption, improved technology, and reduced population.

Fourth, I apply the developed framework using real data at a national level by measuring concepts such as efficiency and equity.

This study also has certain implications for society. First, I stress that the choice of a given feasible sustainability paradigm might clash with criteria such as efficiency, equity, or consistency. As a result, it may require difficult trade-offs. Second, I distinguish among alternative value changes by linking them to a proportion of GDP expenditures on well-established items in national accounting procedures, such as environmental protection, environmental R&D and patents, and development assistance. This lets the numerical results translate easily into policy suggestions. Third, I reveal the consequences of commitments to criteria such as efficiency, equity, and consistency. For example, if global sustainability cannot be achieved by relying on responsibility for nature, responsibility for future and current generations, and aversion to inter- and intra-generational inequality (i.e. secular principles), a change in context may be required (e.g. modified consumption, improved technology, or reduced population), with potential moral problems (e.g. policies based on reducing a nation's population). Alternatively, reference to other values could be suggested (e.g. dignity of non-humans, harmony with nature, stewardship, trusteeship, parsimony, or love of neighbours from religious precepts), with potential development problems (e.g. policies for restraining domestic demand). In other words, I provide a consistent framework to favour choices among value changes and sustainability paradigms to achieve global sustainability. Fourth, by applying this framework to real data at a national level, I quantify the required proportional value changes.

2 Paradigms, concepts, and approaches

In this section, I concisely define the efficiency concepts, equity approaches, and the four sustainability paradigms that I identified in the Introduction.

A sustainability solution is Pareto-efficient if the current generation in *both* OECD and non-OECD countries obtain greater welfare than in the status quo situation. In other words, there are no losers. A sustainability solution is Kaldor–Hicks efficient if current OECD and non-OECD generations *together* obtain greater welfare than in the status quo situation so that the losers can potentially receive compensation from the winners. A sustainability solution reduces inequalities between the current OECD and non-OECD generations in terms of consumption, environment use, or welfare level if the Gini index for one of these variables is smaller than the Gini index for the same variable in the status quo situation; this situation is defined as Gini-equitable. A sustainability solution improves the conditions for the current non-OECD generation in terms of consumption, environment use, or welfare if the minimum value of one variable is larger than its value in the status quo situation; this situation is defined MaxMin-equitable.

The main assumptions behind weak sustainability (i.e. development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs) can be summarised as follows (Schlör et al. 2015): *needs* are used as the unit of measurement; the same weights are used for current and future generations; and there is *unconditional* substitution among current economic, social, and environmental forms of capital at both intra- and inter-generational levels. A sustainability solution is consistent with the weak sustainability paradigm if it is at least Kaldor–Hicks efficient, and if it assumes small aversion to inter- and intra-generational inequality.

A-growth is an ecological and economic strategy focused on indifference to or neutrality about the economic level and growth, with both the economic level and growth considered to be non-robust and unreliable indicators of social welfare and progress (Van den Bergh

2010, 2011). It can be characterised as follows: *welfare* is used as the unit of measurement, as deduced from the aim of moving from wrong prices that result from the many neglected non-market transactions (e.g. informal activities and relationships) and the many unpriced environmental effects to the right prices (i.e. prices that account for both non-market and unpriced values); *different* weights are used for current OECD and non-OECD generations; and substitution between forms of capital is *possible*. A sustainability solution is consistent with the a-growth paradigm if it is Gini-equitable in welfare, and if it assumes small aversion to inter-generational and intra-generational inequality.

De-growth is an ecological and economic perspective based on achieving a socially sustainable and equitable reduction (and eventually stabilisation) of the materials and energy that a society extracts, processes, transports, distributes, consumes, and returns to the environment as wastes (Kallis 2011; Kallis et al. 2012). It can be characterised as follows: *happiness* is the unit of measurement, with a priority on meeting the needs of the poorest individuals, as deduced from the aim of introducing a basic income; the *same* weight is assigned to current and future generations; and substitution among forms of capital is *acceptable*. A sustainability solution is consistent with the de-growth paradigm if it is MaxMin-equitable in welfare and if it assumes a large aversion to inter- and intra-generational inequality.

The main assumptions behind strong sustainability (i.e. a development that allows future generations to access the same amount of natural resources and the same environmental status as the current generation) can be summarised as follows (Jain and Jain 2013): *requirements* for some incommensurable categories as unit of measurement; *possibly* assignment of different weights to current and future generations; and *no* substitution between current or future forms of capital, with natural and physical or social capital considered to be complementary. A sustainability solution is consistent with the strong sustainability paradigm if it is Gini-equitable for consumption and environment use, and if it assumes a large aversion to inter- and intra-generational inequality.

Utilitarianism, in the version I consider here (Harsanyi 1982) can be characterised as follows: equally weighting everyone's welfare, with welfare defined as the satisfaction of rational, well-informed, and self-interested preferences, by maximising the total social welfare. A sustainability solution is consistent with the utilitarian approach if it is Pareto-efficient or Kaldor–Hicks efficient and if it assumes a small aversion to inter- and intra-generational inequality.

Egalitarianism, in the main three alternative versions that I focus on here, can be summarised as follows: it involves (1) levelling of resources or primary goods, as in Dworkin (1981); (2) equalising capabilities, as in Sen (1993); or (3) equalising opportunities for welfare, as in Arneson (1989). A sustainability solution is consistent with these egalitarian approaches if it assumes a large aversion to inter- and intra-generational inequality, and if it is Gini-equitable in consumption or environment use for case 1, Gini-equitable in consumption and environment use for case 2, and Gini-equitable in welfare for case 3.

Contractarianism, in the version considered here (Rawls 1971), can be characterised as follows: it arranges social and economic inequalities to the greatest benefit of the least advantaged people by opening offices and positions to everybody. A sustainability solution is consistent with the contractarian approach if it is MaxMin-equitable for consumption, environment use, or welfare, and if it assumes a large aversion to inter- and intra-generational inequality.

Note that I have disregarded libertarian approaches, both in terms of positive rights (Lomasky 1987) and negative rights (Nozick 1974), because it is arguable whether future generations or nature have rights in this context (Gosseries 2008). Moreover, sustainability solutions in terms of value changes could be turned into policy suggestions; for example, a sense of responsibility for nature, for future generations, or for the current generation could be translated into the proportion of the income allocated to environmental protection, environmental R&D, and aids for poor people. Finally, equality is assumed to be instrumental (Kershnar and Purves 2016), since a value is attached to consequences for people.

3 The model

This section provides simple formalisations for the four sustainability paradigms identified in Sect. 2 with the goal of requiring as little data as possible about representative individuals in OECD and non-OECD countries. For simplicity, and with full recognition that this approach ignores some exceptions, I have used the subscript N (northern hemisphere) to label parameters for OECD countries and the subscript S (southern hemisphere) for non-OECD countries. Appendix 1 lists all the abbreviations used in this model.

Let us assume that E_N and E_S identify the per capita use of the global environment by the current OECD and non-OECD generations, respectively. The per capita equilibrium level consistent with the current world population is η. Let us assume that X_N, X_S, and X_F identify the per capita consumption levels in the OECD current generation, non-OECD current generation, and the future generations, respectively. Thus, the use of the environment for the OECD current generation is given by $E_N = \theta_N X_N$, for the non-OECD current generation is given by $E_S = \theta_S X_S$, and for the future generations is given by $E_F = \theta_F X_F$, where θ_N, θ_S, and θ_F represent the use of the environment for each consumption unit for the current OECD generation, current non-OECD generation, and the future generation, respectively: θ_N and θ_S will be set at current values based on the current technology, and then simulated as smaller than current values to analyse the impacts of technological improvement.

Two main sustainability conditions can be formalised. The weighted sustainability condition requires that the use of the environment must be weighted according to the proportions of the global population in the OECD and non-OECD countries (p_N and p_S, respectively):

$$E_C = p_N E_N + p_S E_S$$

where E_C stands for the total weighted use of the environment by the current generation in both OECD and non-OECD countries. The non-weighted sustainability condition requires that the use of the environment must be averaged between the representative individuals in the OECD and non-OECD countries:

$$E_C = 1/2 E_N + 1/2 E_S.$$

Thus, in terms of consumption levels, these sustainability conditions become, respectively:

$$\eta = E_C = p_N \theta_N X_N + p_S \theta_S X_S$$

And

$$\eta = E_C = 1/2 \theta_N X_N + 1/2 \theta_S X_S.$$

The non-weighted sustainability condition will be used for the strong sustainability paradigm, and the weighted sustainability condition for the other sustainability paradigms. Let us assume that the utility for the future generations (U_F) depends only on the consumption level:

$$U_F = X_F^{\alpha_F}.$$

This is a Cobb–Douglas utility function in which α_F represents the future preference for consumption. Indeed, I have *optimistically* assumed that socioeconomic development will gradually raise non-OECD countries to the same level as the OECD countries so that there is no future non-OECD generation and, consequently, future OECD countries cannot be concerned about non-OECD countries. Next, I have assumed that the use of the global environment is in its long-run equilibrium so that people do not need to feel a responsibility to preserve the environment for subsequent generations. See Supplementary Materials I for a discussion of the stability of pro-environmental equilibria. Let us assume that the welfare of the current non-OECD generation (U_S) depends on their consumption level, the use of the environment, and the welfare of the future generation:

$$U_S = X_S^{\alpha_S} E_S^{-\beta_S} U_F^{\gamma_S}.$$

This is a Cobb–Douglas utility function in which α_S represents the preference for consumption, β_S represents the degree of concern over use of the environment, and γ_S represents the degree of concern for future generations. Indeed, the current non-OECD generation is less affluent and cannot afford to be heavily concerned with people from OECD countries. Let us assume that the welfare of the current OECD generation depends on their consumption level, their use of Earth resources, the welfare of the future generation, and the welfare of the current non-OECD generation:

$$U_N = X_N^{\alpha_N} E_N^{-\beta_N} U_F^{\gamma_N} U_S^{\delta_N}.$$

This is a Cobb–Douglas utility function in which α_N represents the preference for consumption, β_N represents concern over the use of Earth resources, γ_N represents concern for future generations, and δ_N represents the concern for the current non-OECD generation (Lauwers 2012). In other words, both OECD and non-OECD countries are assumed to be concerned about their own environment (i.e. E_N and E_S, respectively) rather than about the overall world environment (i.e. $E_C = p_N\ E_N + p_S\ E_S$). Indeed, non-OECD countries might not be concerned about the environment in OECD countries, whereas OECD countries are assumed to be concerned about consequences of the use of the environment on the welfare level in non-OECD countries. Moreover, the concern for the total environment seems to be more plausible in the case of a specified common environment (e.g. a closed sea such as the Baltic Sea) to be shared by a specified group of countries. Appendix 2 presents a formalisation of this analysis in the case of a shared common environment. Finally, maximising the total welfare first and then accounting for sustainability conditions (rather than in the opposite sequence) would lead to higher production and consumption in the more efficient OECD countries, at levels even larger than current production and consumption, with sustainability conditions for the weak sustainability and a-growth paradigms being less feasible.

Note that a logarithmic transformation of the Cobb–Douglas utility functions permits analytical solutions. Moreover, in addition to being affected by nature, welfare could be directly affected by other types of capital such as social, physical, and human capital, where these forms of capital, like nature, contribute to achieving a given consumption level. Finally, each parameter attached to an item of the Cobb–Douglas utility function (e.g. α to consumption, β to the environment, γ to the welfare of future generations, δ to welfare of the current non-OECD generation) can be related to the proportion of the budget spent to purchase it. Let us assume that a representative individual in the current generation is concerned about welfare inequality between OECD and non-OECD countries:

$$U_{\mathrm{C}} = \left[(p_{\mathrm{N}} U_{\mathrm{N}})^{1-\varepsilon} + (p_{\mathrm{S}} U_{\mathrm{S}})^{1-\varepsilon}\right]^{1/(1-\varepsilon)}.$$

This is a constant elasticity of substitution utility function in which ε is the degree of aversion to intra-generational inequality (Asheim et al. 2012). Thus, the overall utility is given by:

$$U = \left[U_{\mathrm{C}}^{1-\zeta} + U_{\mathrm{F}}^{1-\zeta}\right]^{1/(1-\zeta)}.$$

This is a constant elasticity of substitution utility function in which ζ is the degree of aversion to inter-generational inequality. Alternatively, a representative individual in the current generation could be concerned about inequality in use of the global environment between OECD and non-OECD countries:

$$W_{\mathrm{C}} = \left[E_{\mathrm{N}}^{1-\varepsilon} + E_{\mathrm{S}}^{1-\varepsilon}\right]^{1/(1-\varepsilon)}.$$

Thus, the overall welfare would be given by:

$$W = \left[E_{\mathrm{C}}^{1-\zeta} + E_{\mathrm{F}}^{1-\zeta}\right]^{1/(1-\zeta)}.$$

Note that the time discount rate is assumed to be 0, as this is the only value that is consistent with long-run equilibria. Moreover, each social utility or welfare function can be linked to an Atkinson inequality index, in which parameters ε and ζ have the same meaning. Finally, extreme values of ε and ζ (i.e. at 0 and 1) permit analytical solutions.

Many theoretical definitions of the four sustainability paradigms can be suggested (Aznar-Marquez and Ruiz-Tamarit 2016). Here, I will apply the analytical definitions summarised in Table 1. Note that the "grand simplification" criticised by Norton (2005) (i.e. the preferences and needs of people in the future are unknown, present prices reflect future values, and resources are substitutable for each other; thus, sustainability boils down to

Table 1 The analytical definitions of the four sustainability paradigms

Paradigm	Analytical definition
Weak sustainability	Max U s.t. $U_{\mathrm{F}} \geq U_{\mathrm{C}}$
A-growth	Max U s.t. $E_{\mathrm{C}} \leq E_{\mathrm{F}}$
De-growth	Min X_{C} s.t. $U_{\mathrm{F}} \geq U_{\mathrm{C}}$
Strong sustainability	Max W s.t. $E_{\mathrm{C}} \leq E_{\mathrm{F}}$

U, overall utility in terms of consumption; U_{F}, utility for the future generation; U_{C}, total weighted utility for the current generation in both developed and developing countries; E_{C}, total weighted use of the environment by the current generation in both developed and developing countries; E_{F}, use of the environment by the future generation; X_{C}, total weighted consumption by the current generation in both developed and developing countries; W, overall welfare in terms of the environment maintaining capital stocks across time) and the "(strong) economic sustainability" suggested by Norton (2005) are close to the weak and strong sustainability paradigms formalised in Table 1, respectively. In contrast, the environmental ethics of Norton's "normative sustainability" applies to all sustainability paradigms. In particular, OECD and non-OECD countries are both assumed to adopt a cooperative rather than a non-cooperative attitude, leading (for example) to a Nash equilibrium. This is realistic because currently, there is no coalition of OECD countries playing against the interests of non-OECD countries. Moreover, a non-cooperative context seems to be more plausible in the case of a specified group of countries exploiting a common environment. See Appendix 2 for a formalisation of this analysis in the case of a shared common environment. Finally, referring to a non-cooperative context disregards the aversion to inter-generational inequality.

Note that the analytical definition of de-growth does not depend on E_N. This is consistent with the main critiques of this paradigm. Moreover, the four sustainability paradigms share couples of conditions: for example, Max U is shared by weak sustainability and a-growth; $U_F \geq U_C$ is shared by weak sustainability and de-growth; and $E_C \leq E_F$ is shared by a-growth and strong sustainability. Finally, the analytical definition of strong sustainability assumes that the parameters ε and ζ are set at 1. This is consistent with the main feature of this paradigm (i.e. maximum aversion to inequality).

By solving for the sustainability requirements for consumption level and environment use in non-OECD countries, and by using these expressions as inputs for the maximisation or minimisation problems that identify the four sustainability paradigms, it becomes possible to characterise these problems in terms of the variables for the OECD countries, for which solutions for X_N and E_N represent solutions for the world that meet global sustainability conditions.

Note that weak inequalities will be solved as equalities. Moreover, because other changes could affect the equilibria, a *ceteris paribus* analysis will be performed. Finally, dynamic stability conditions will not be considered, and static sustainability equilibria will be obtained.

Some methodological remarks are noteworthy here. The model employed in this study (i.e. the utility functions used to represent preferences) can be justified both theoretically and empirically.

In terms of its *theoretical* foundations, one should use a Cobb–Douglas utility function, which is based on the assumption that the preferences for a set of items are likely to be almost constant. Here, values such as a sense of responsibility for nature (β), for future generations (γ), or for the current generation in developing countries (δ) are likely to change slowly, if at all. Consequently, an almost constant proportion of the total budget will be allocated to these items (here, to environmental protection, green R&D and patents, and development assistance). Whenever items for which preferences are expressed can be considered to be pure substitutes, pure complements, or mixed substitutes and complements (here, the welfare of current and future generations), one should use a constant elasticity of substitution utility function. In terms of the model's *empirical* foundations, the proportions of the total budget allocated to environmental protection, green R&D and patents, and development assistance (below, obtained from national statistics and expressed as a percentage of GDP) can be used to estimate all parameters of the Cobb–Douglas utility function (i.e. β, γ, and δ, once the values have been normalised with respect to α, as described in Sect. 4). This can be done by relying on the optimal solution of the usual utility maximisation problem subject to an income constraint in the case of a Cobb–Douglas utility function. For instance, the optimal expenditure for an item associated with β in the Cobb–Douglas utility function is given by $[\beta/(\alpha+\beta+\gamma+\delta)]\ y$, where y is the available income. The degree of aversion to intra- and inter-generational inequality (below, assumed to depict alternative scenarios) can be used to estimate all parameters of the constant elasticity of substitution utility function (i.e. ε and ζ) by relaying on the one-to-one relationship between the Atkinson inequality measure and a constant elasticity of substitution utility function, in which welfare increases if inequality decreases. In particular, the Atkinson inequality measure is given by $1-[(1/n)\sum(x_i/x^*)^{1-\varepsilon}]^{1/(1-\varepsilon)}$, with x_i representing the value of item i, x^* representing the mean of the total of n items, and ε representing the inequality aversion parameter.

4 Data and normalisations

Some parameters of the model developed in Sect. 3 can be directly estimated. In particular, the proportions of the world's current population in OECD and non-OECD countries, based on World Bank world development indicators (http://data.worldbank.org) data for 2012, are $p_N=0.18$ and $p_S=0.82$. If the per capita use of the global environment is measured by the ecological footprint (i.e. the biologically productive area needed to provide everything an individual uses), sustainability of a representative individual for the world at the current population level requires E_F to be at $\eta=1.7$ ha (http://www.footprintnetwork.org), whereas the values for use of the environment in OECD and non-OECD countries, based on data for 2012, are 5.74 and 2.15 ha, respectively. The actual individual consumption as a percentage of GDP is available for each OECD country, with an average at 71.1%. Unfortunately, comparable data are not available for non-OECD countries, although their average is likely to be larger. Without significant loss of generality, I will assume that the per capita consumption is measured by the per capita income (i.e. GDP in USD, based on purchasing power parity [PPP]). Indeed, postponed consumption (as saving or investment) affects the welfare of future generations, but this welfare increase contributes to the current generation's utility (i.e. both U_N and U_S depend on U_F). Moreover, consumption of imported goods (typically, in OECD countries) increases welfare where they are consumed, but their production might increase the use of the environment and so reduce welfare where they are produced and then exported (typically, in non-OECD countries). However, this welfare decrease in non-OECD countries contributes to the utility for OECD countries (i.e. U_N depends on U_S). Finally, net exports equal net imports at the world level. Thus, the per capita consumption levels in OECD and non-OECD countries, based on world development indicators data for 2012, are US$36 727 GDP PPP and US$8216 GDP PPP, respectively. The current OECD generation's aversion to inequality for the current non-OECD generation (ε) and the current generation's aversion to inequality for future generations (ζ) are both in the range [0.01, 0.99].

Some parameters of the model developed in Sect. 3 require additional assumptions or manipulations. In particular, the future population was normalised to 1. In other words, I compare representative individuals for the current and future world, with a change in the future population depicted by a change in the sustainable per-capita E_F. Future consumption preferences are assumed to converge towards the preferences of the current OECD generation (i.e. $\alpha_F=\alpha_N$). This assumption seems to be consistent with the observed aspiration of the current non-OECD generation, whereas a future preference for consumption at a level that equals the average of current preferences seems to be more plausible in the case of a specified group of countries at similar levels of development. See Appendix 2 for formalisation of this analysis in the case of a shared common environment.

The future generation achieves sustainability by relying on the environmental technology currently being applied by the OECD countries (i.e. $\theta_F = \theta_N$). In other words, complete technology transfer between developed and developing nations is *optimistically* assumed to be implemented in the future. Indeed, some technological convergence is likely to occur, although it is impossible to quantify the degree of this convergence. Moreover, a future technology that represents an average of the capabilities of current technologies seems to be more plausible in the case of a specified group of countries at similar levels of development. See Appendix 2 for formalisation of this analysis in the case of a shared common environment. Finally, this assumption does not affect the solutions for the a-growth and strong sustainability paradigms, but makes the solutions for the weak sustainability and de-growth paradigms less feasible.

The remaining parameters of the model developed in Sect. 3 can be indirectly estimated. In particular, the benchmark scenario is characterised by OECD countries attaching the same importance (i.e. the same budget share) to consumption level, environmental preservation, the welfare of future generations, and the welfare of people in non-OECD countries; in this analysis, the budget share for consumption represents the parameter with the maximum budget share (i.e. the preference for consumption is realistically assumed not to be smaller than the concerns for the other issues), with the budget shares for all parameters summing up to 1. On this basis, I have fixed α_N at 0.25, and have normalised all other parameters with respect to this value (i.e. the observed budget shares are multiplied by 0.25). The OECD concern about the use of the environment (β_N) is based on the assumption that 6.8% of GDP is devoted to the environment in OECD countries. This value was calculated by multiplying the observed average government expenditure on environmental protection as a percentage of GDP in OECD countries (i.e. 1.7% in the OECD data; http://www.oecd-ilibrary.org) by 4, to account for both public and private expenditures as well as for both direct and indirect expenditures. That is, this assumes equal expenditures for each of these four categories of expenditure. Similarly, the current OECD generation's concern for future generations (γ_N) is based on the average value of 4.8% of GDP devoted to green R&D and patents in OECD countries. This percentage was calculated by multiplying the average observed expenditure on environmental R&D and patents as a percentage of GDP observed in OECD countries (i.e. 2.4% in OECD data; http://www.oecd-ilibrary.org) by 2, to take into account both direct and indirect expenditures. That is, this assumes equal expenditures for public and private expenditures. Similarly, the current OECD generation's concern for the current non-OECD generation (δ_N) is based on the assumption that 1.2% of GDP in OECD countries is devoted to providing development assistance. This is calculated by multiplying the average observed official government expenditure on development assistance as a percentage of GDP in OECD countries (i.e. 0.3% in OECD data; http://www.oecd-ilibrary.org) by 4 to account for both public and private expenditures as well as both direct and indirect expenditures. That is, this assumes equal expenditures for each of these four categories of expenditure.

To facilitate comparisons between the numerical simulations, without significant loss of generality, I will normalise $\beta_N = \gamma_N = \delta_N = 0.01$ to represent an average share of GDP of 4% (i.e. $[0.01/0.25] \times 100\%$). Unfortunately, comparable data are not available for non-OECD countries. Without significant loss of generality, I will assume that $\alpha_S = \alpha_N$ (i.e. since only three parameters are inputs for U_S, this implies a greater importance attached to consumption for people in non-OECD countries) and $\beta_S = \gamma_S = 0.005$ (i.e. the current non-OECD generation's concern over use of Earth resources and concern for future generations is assumed to be half of what is estimated for the current OECD generation). Indeed, all these figures are likely to be tiny but positive.

5 Results

This section, for the sustainability paradigms described using the model developed in Sect. 3, will provide analytical solutions for cases based on extreme parameter values, and identify numerical solutions for cases based on the data and normalisations described in Sect. 4. Appendix 3 presents statistical analyses to check for the significance and size of the five main secular environmental ethics for sustainability (i.e. β, γ, δ, ε, and ζ), by relying on the same dataset discussed in Sect. 4 and the formulas introduced in Sect. 3. I will do this by relying on graphs that represent the relevant conditions within the whole problem domain for the OECD consumption level and use of the environment: X_N in [0, 36.727] and E_N in [0, 5.74], where 36.727 and 5.74 are the current values. These solutions are then characterised in terms of the alternative efficiency and equity approaches by referring to the following current (i.e. status quo) values: $X_F = 10.876$, $E_F = 1.7$, $U_F = 1.81$, $X_C = 13.348$, $E_C = 2.79$, and $U_C = 1.82$.

Some methodological remarks are noteworthy here. The purpose of the analysis is *not* to explain many (past) observations of the same phenomenon and to predict its (future) dynamics, but rather to estimate the relative effectiveness of the (future) actions (here, value changes) required to achieve sustainability in a real context identified by a single (present) observation (here, the sustainability status of the economies of OECD and non-OECD countries). Consequently, the usual processes of validation and testing must be reinterpreted or rephrased.

The usual validation procedures for choosing a model are to identify a sub-sample of the observations; endogenously parameterise the model (e.g. by choosing parameter values to minimise the distance between the observed or empirical values and the simulated or theoretical values); and evaluate the estimation error of the model (i.e. measure the extent to which the model explains the data in the sub-sample once it has been parameterised). This approach cannot be applied in the present context because the sample is too small and unbalanced (i.e. 145 countries including both 33 OECD and 112 non-OECD countries) for a statistical analysis based on two sub-samples (i.e. for both OECD and non-OECD countries) to produce a reliable estimation of 9 parameters (i.e. α_N, β_N, γ_N, δ_N, α_S, β_S, γ_S, ε, and ζ) in a nonlinear model. Instead, the model explains a single observation with no error, since the parameters are exogenously calculated to depict this observation. Note that the logic of the algorithms and their self-consistency is corroborated, since both the analytical and the numerical solutions are obtained using the same software (i.e. Mathematica).

Next, the usual procedures for testing a model (i.e. identify an out-of-sample dataset and compare it with the predictions of the previously parameterised model) cannot be applied here. Indeed, there are no future observations of variables (i.e. X and E) with changed values (i.e. $\Delta\beta_N$, $\Delta\gamma_N$, $\Delta\delta_N$, $\Delta\beta_S$, $\Delta\gamma_S$, $\Delta\varepsilon$, and $\Delta\zeta$) that could be used to perform any statistical analysis. Instead, the model predicts the future sustainability scenarios with no error, since calculations are presented over the whole variable space to ensure the absence of alternative solutions. Note that the reliability of the presented solutions is confirmed, since the accuracy and precision goals of Mathematica were set at 10 in this analysis (i.e. the calculation algorithm stops searching for solutions only if the relative distance from the root is smaller than 10^{-10}; in other words, the error tolerances for the presented solutions are smaller than 10^{-10}).

In other words, although the estimated parameters can be compared in terms of significance and plausibility (e.g. from the statistical analysis presented in Appendix 3, α_N and α_S are plausible and significant; β_N and β_S are significant, but implausibly large; γ_N, γ_S, and δ_N

are plausible, but non-significant; ε is plausible, but non-significant; and ζ is significant, but implausibly large), a statistical analysis cannot produce reliable parameter values to be used in numerical simulations; thus, a dimensional analysis is performed instead. In particular, since the focus is on the relative effectiveness (ability to achieve sustainability) of value changes such as responsibility towards the environment (β), towards future generations (γ), towards the current generation in developing countries (δ), aversion to inequality within the current generation (ε), and aversion to inequality between current and future generations (ζ), all items associated with these parameters (i.e. E_S or E_N, U_F, U_N, and U_S) are one-digit numbers (i.e. a consistent set of units is applied). Note that X_S is also a one-digit number, whereas X_N is a two-digit number, although it is often around 10 and always smaller than 12.68 in feasible solutions. However, this irregularity is non-significant, since the associated parameter (α) is normalised to 0.25.

5.1 Corner solutions

In this section, I search for feasible solutions arising from changes in a single preference parameter to determine whether a single change can achieve sustainability. To do so, I measure feasibility in terms of acceptable welfare losses in OECD and non-OECD countries.

For a situation in which there is no concern for nature, future generations, and non-OECD countries (i.e. $\beta_N = \gamma_N = \delta_N = 0$) in OECD countries, and in which there is no concern for nature and future generations (i.e. $\beta_S = \gamma_S = 0$) in non-OECD countries, and for which the current generation's aversion to inequality for the current non-OECD generation and the current generation's aversion to inequality for future generations are both at their minimum (i.e. $\varepsilon = \zeta = 0$), the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \geq U_C$),

$$X_N = \frac{\eta\alpha_N}{\theta_N\left(p_N\alpha_N + p_S\alpha_S\right)} \quad \text{and} \quad X_N \leq \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \leq E_F$),

$$X_N = \frac{\eta\alpha_N}{\theta_N\left(p_N\alpha_N + p_S\alpha_S\right)} \quad \text{and} \quad p_N\theta_N X_N + p_S\theta_S X_S \leq \eta$$

For de-growth (i.e. $U_F \geq U_C$ and $X_C \leq X_F$),

$$X_N \leq \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N X_N + p_S X_S \leq X_F$$

For strong sustainability (i.e. first-order conditions for Max W and $E_C \leq E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N\theta_N X_N + p_S\theta_S X_S \leq \eta.$$

Figure 1 illustrates the *numerical* solutions for these equations based on empirical data.

For a situation in which there is no concern for future generations and non-OECD countries (i.e. $\gamma_N = \delta_N = 0$) in OECD countries, and for which there is no concern for future generations (i.e. $\gamma_S = 0$) in non-OECD countries, and for which the current generation's aversion to inequality for the current non-OECD generation and the current generation's

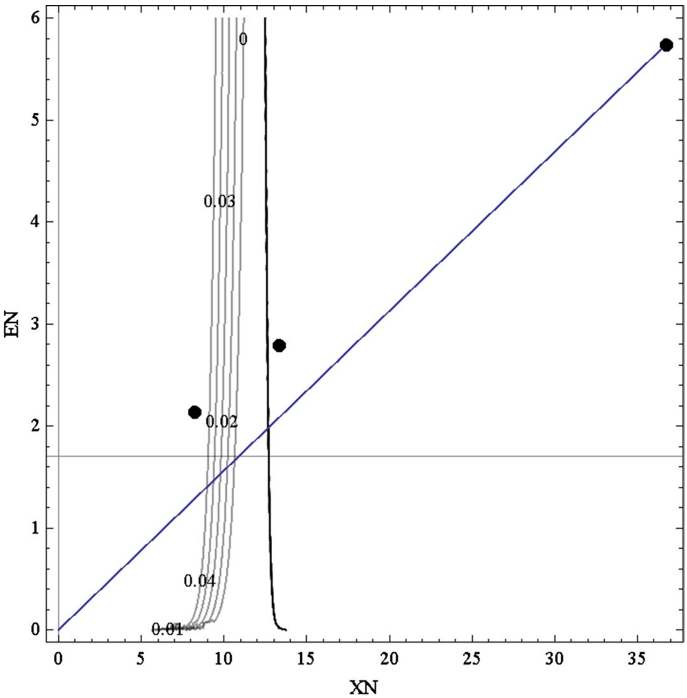

Fig. 1 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on current preferences: $\alpha_N=\alpha_S=0.25$, $\beta_N=\gamma_N=\delta_N=0.01$, $\beta_S=\gamma_S=0.005$, $\varepsilon=\zeta=0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F-U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve to the right of this cluster represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \le E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

aversion to inequality for future generations are both at their minimum (i.e. $\varepsilon=\zeta=0$), the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \ge U_C$),

$$X_N = \frac{\eta(\alpha_N-\beta_N)}{\theta_N\left[p_N(\alpha_N-\beta_N)+p_S(\alpha_S-\beta_S)\right]} \quad \text{and}$$

$$X_N \le \exp^{\frac{U_F}{(\alpha_N-\beta_N)p_N}}\left(p_N\theta_N\right)^{\frac{\beta_N p_N}{(\alpha_N-\beta_N)p_N}}\left(p_S\theta_S\right)^{\frac{\beta_S p_S}{(\alpha_N-\beta_N)p_N}} X_S^{-\frac{(\alpha_S-\beta_S)p_S}{(\alpha_N-\beta_N)p_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \le E_F$),

$$X_N = \frac{\eta(\alpha_N-\beta_N)}{\theta_N\left[p_N(\alpha_N-\beta_N)+p_S(\alpha_S-\beta_S)\right]} \quad \text{and} \quad p_N\theta_N X_N + p_S\theta_S X_S \le \eta$$

For de-growth (i.e. $U_F \ge U_C$ and $X_C \le X_F$),

$$X_N \le \exp^{\frac{U_F}{(\alpha_N-\beta_N)p_N}}\left(p_N\theta_N\right)^{\frac{\beta_N p_N}{(\alpha_N-\beta_N)p_N}}\left(p_S\theta_S\right)^{\frac{\beta_S p_S}{(\alpha_N-\beta_N)p_N}} X_S^{-\frac{(\alpha_S-\beta_S)p_S}{(\alpha_N-\beta_N)p_N}} \quad \text{and} \quad p_N X_N + p_S X_S \le X_F$$

For strong sustainability (i.e. first-order conditions for Max W and $E_C \le E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N\theta_N X_N + p_S\theta_S X_S \le \eta.$$

Figure 2 illustrates the *numerical* solutions based on empirical data.

For a situation in which there is no concern for nature and for non-OECD countries (i.e. $\beta_N = \delta_N = 0$) in OECD countries, and in which there is no concern for nature (i.e. $\gamma_S = 0$) in non-OECD countries, and in which the current generation's aversion to inequality for the current non-OECD generation and the current generation's aversion to inequality for future generations are both at their minimum (i.e. $\varepsilon = \zeta = 0$), the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \ge U_C$),

$$X_N = \frac{\eta\alpha_N}{\theta_N\left(p_N\alpha_N + p_S\alpha_S\right)} \quad \text{and} \quad X_N \le \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \le EF$),

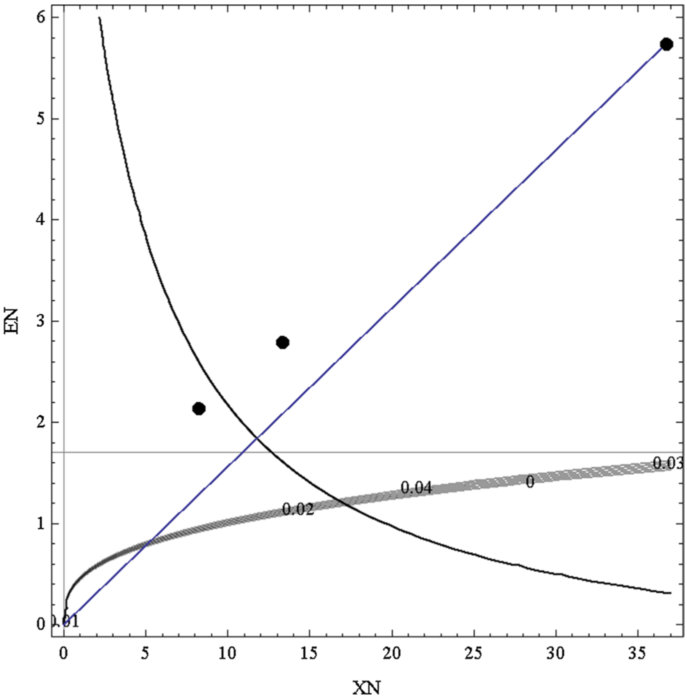

Fig. 2 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on the perceived responsibility for nature: $\alpha_N = \alpha_S = 0.25$, $\beta_N = \beta_S = 0.73$, $\gamma_N = \delta_N = 0.01$, $\gamma_S = 0.005$, $\varepsilon = \zeta = 0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from top to bottom. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \le E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

$$X_N = \frac{\eta \alpha_N}{\theta_N (p_N \alpha_N + p_S \alpha_S)} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta$$

For de-growth (i.e. $U_F \geq U_C$ and $X_C \leq X_F$),

$$X_N = \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} U_F^{-\frac{\gamma_N p_N + \gamma_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N X_N + p_S X_S \leq X_F$$

For strong sustainability (i.e. first-order conditions for Max W and $E_C \leq E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta.$$

Figure 3 illustrates the *numerical* solutions based on empirical data.

For a situation in which there is no concern for nature and future generations (i.e. $\beta_N = \gamma_N = 0$) in OECD countries, and in which there is no concern for nature and future generations (i.e. $\beta_S = \gamma_S = 0$) in non-OECD countries, and in which the current generation's aversion to inequality for the current non-OECD generation and the current

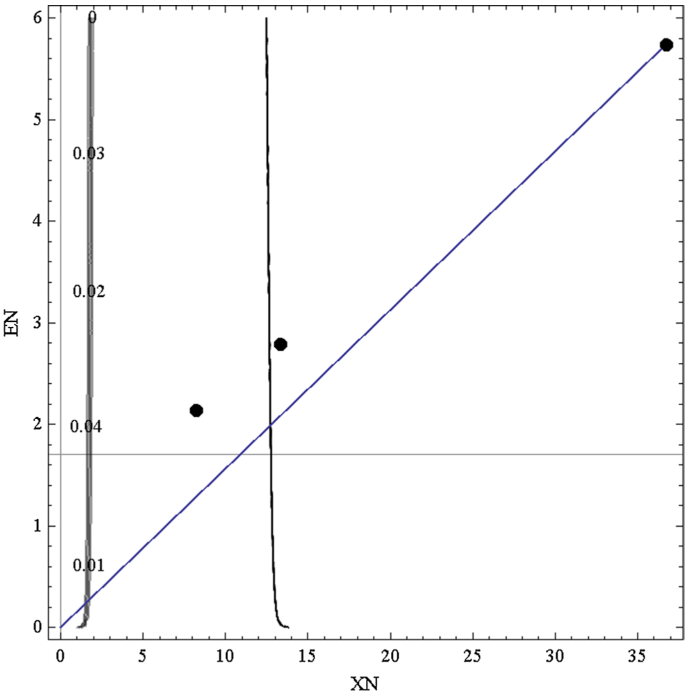

Fig. 3 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on a concern for future generations: $\alpha_N = \alpha_S = 0.25$, $\gamma_N = \gamma_S = 0.73$, $\beta_N = \delta_N = 0.01$, $\beta_S = 0.005$, $\varepsilon = \zeta = 0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve to the right of this cluster represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

generation's aversion to inequality for future generations are both at their minimum (i.e. $\varepsilon = \zeta = 0$), the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \geq U_C$),

$$X_N = \frac{\alpha_N \eta \ln[X_S]}{\theta_N (p_N \delta_N + p_N \alpha_N \ln[X_S] + p_S \alpha_S \ln[X_S])} \quad \text{and} \quad X_N \leq \alpha_S^{-\frac{\delta_N}{\alpha_N}} \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \ln[X_S]^{-\frac{\delta_N}{\alpha_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \leq E_F$),

$$X_N = \frac{\alpha_N \eta \ln[X_S]}{\theta_N (p_N \delta_N + p_N \alpha_N \ln[X_S] + p_S \alpha_S \ln[X_S])} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta$$

For de-growth (i.e. $U_F \geq U_C$ and $X_C \leq X_F$),

$$X_N = \alpha_S^{-\frac{\delta_N}{\alpha_N}} \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \ln[X_S]^{-\frac{\delta_N}{\alpha_N}} \quad \text{and} \quad p_N X_N + p_S X_S \leq X_F$$

For strong sustainability (i.e. first-order conditions for Max W and $E_C \leq E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta.$$

Figure 4 illustrates the *numerical* solutions based on empirical data.

For a situation in which there is no concern for nature, future generations, and non-OECD countries (i.e. $\beta_N = \gamma_N = \delta_N = 0$) in OECD countries, and in which there is no concern for nature and future generations (i.e. $\beta_S = \gamma_S = 0$) in non-OECD countries, and in which the current generation's aversion to inequality for the current non-OECD generation and the current generation's aversion to inequality for future generations are at their maximum (i.e. $\varepsilon = 1$ so $p_N\ U_N = p_S\ U_S$) and at their minimum (i.e. $\zeta = 0$), respectively, the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \geq U_C$),

$$X_N = X_S^{\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad X_N \leq \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \leq E_F$),

$$X_N = X_S^{\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta$$

For de-growth (i.e. $U_F \geq U_C$ and $X_C \leq X_F$),

$$X_N = \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N X_N + p_S X_S \leq X_F$$

For strong sustainability (i.e. first-order conditions for Max W and $E_C \leq E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta.$$

Figure 5 illustrates the *numerical* solutions based on empirical data.

For a situation in which there is no concern for nature, future generations, and non-OECD countries (i.e. $\beta_N = \gamma_N = \delta_N = 0$) in OECD countries, and in which there is no

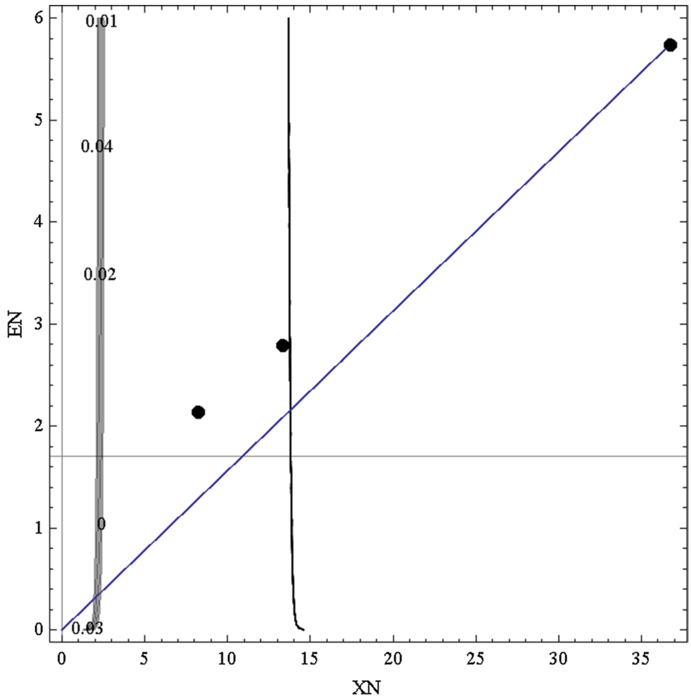

Fig. 4 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on a concern for non-OECD countries: $\alpha_N = \alpha_S = 0.25$, $\delta_N = 0.73$, $\beta_N = \gamma_N = 0.01$, $\beta_S = \gamma_S = 0.005$, $\varepsilon = \zeta = 0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve to the right of this cluster represents the first-order conditions for Max U. The increasing straight line represents the border condition for $EF \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

concern for nature and future generations (i.e. $\beta_S = \gamma_S = 0$) in non-OECD countries, and in which the current generation's aversion to inequality for the current non-OECD generation and the current generation's aversion to inequality for future generations are at their minimum (i.e. $\varepsilon = 0$) and at their maximum (i.e. $\zeta = 1$ so $U_C = U_F$), respectively, the *analytical* solutions for the four sustainability paradigms are as follows:

For weak sustainability (i.e. first-order conditions for Max U and $U_F \geq U_C$),

$$X_N = \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad X_N \leq \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}}$$

For a-growth (i.e. first-order conditions for Max U and $E_C \leq E_F$),

$$X_N = \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N \theta_N X_N + p_S \theta_S X_S \leq \eta$$

For de-growth (i.e. $U_F \geq U_C$ and $X_C \leq X_F$),

$$X_N = \exp^{\frac{U_F}{\alpha_N p_N}} X_S^{-\frac{\alpha_S p_S}{\alpha_N p_N}} \quad \text{and} \quad p_N X_N + p_S X_S \leq X_F$$

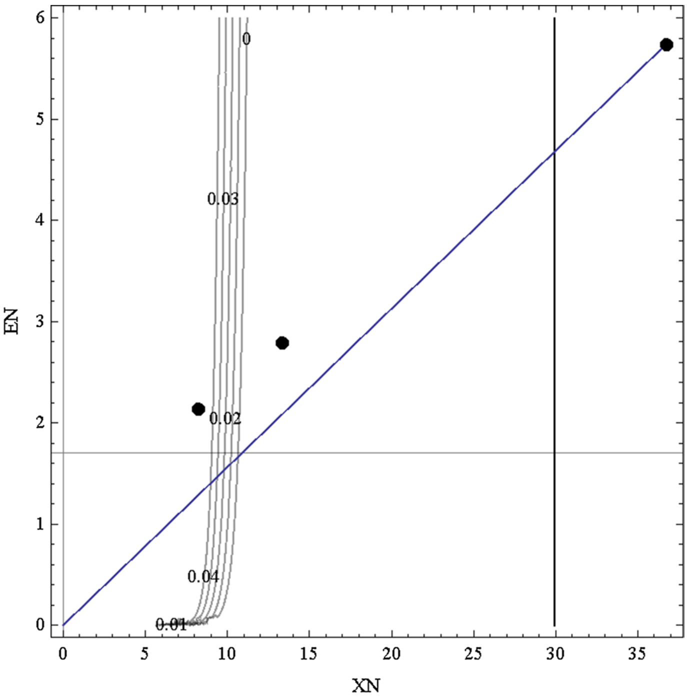

Fig. 5 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on aversion to inequality for non-OECD countries: $\alpha_N = \alpha_S = 0.25$, $\beta_N = \gamma_N = \delta_N = 0.01$, $\beta_S = \gamma_S = 0.005$, $\varepsilon = 0.99$, $\zeta = 0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve to the right of this cluster represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

For strong sustainability (i.e. first-order conditions for Max W and $E_C \leq E_F$),

$$X_N = \frac{\eta}{\theta_N} \quad \text{and} \quad X_S = \frac{\eta}{\theta_S} \quad \text{and} \quad p_N\theta_N X_N + p_S\theta_S X_S \leq \eta.$$

Figure 6 illustrates the *numerical* solutions based on empirical data.

Figures 1, 2, 3, 4, 5 and 6 show that there are no solutions for weak sustainability, apart from the case with (extreme) responsibility for nature, whereas the other three sustainability paradigms always have solutions. Table 2 suggests that, with current preferences, a-growth and strong sustainability are slightly feasible, although these solutions are Gini-equitable for consumption, environment use, and welfare. Responsibility for nature makes all paradigms unfeasible. As expected, concern for future generations makes a-growth and strong sustainability feasible, and solutions are also MaxMin-equitable for welfare; Gini-equitable for consumption, environment use, and welfare; and Pareto-efficient. Surprisingly, a concern for non-OECD countries makes a-growth and strong sustainability moderately feasible, and solutions are Kaldor–Hicks efficient and Gini-equitable for consumption and environment use. Aversion to inequality for non-OECD countries makes a-growth and strong sustainability moderately and slightly feasible, respectively, with a reduction

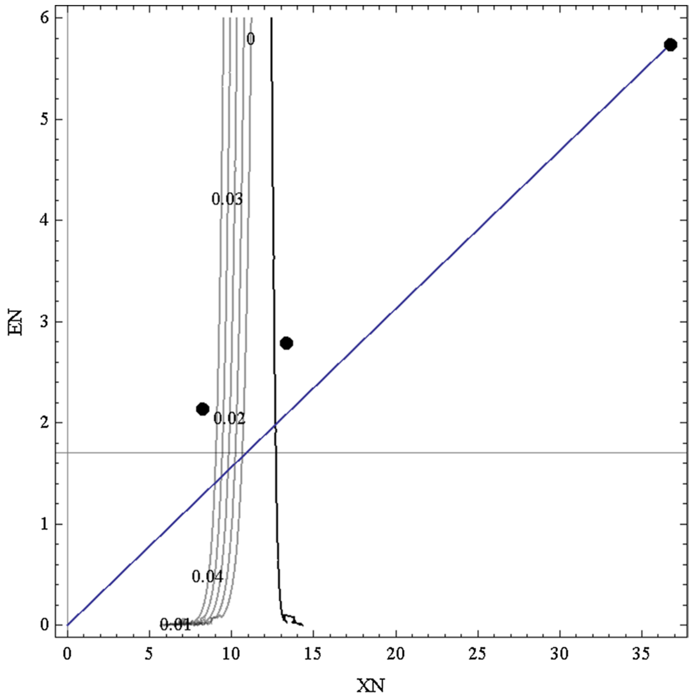

Fig. 6 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on aversion to inequality for future generations: $\alpha_N = \alpha_S = 0.25$, $\beta_N = \gamma_N = \delta_N = 0.01$, $\beta_S = \gamma_S = 0.005$, $\varepsilon = 0.01$, $\zeta = 0.99$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve to the right of this cluster represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

of welfare by 5 and 16% for OECD and non-OECD countries, respectively, for a-growth, and by 25 and 5% for strong sustainability, respectively. In addition, all strong sustainability solutions are Gini-equitable for consumption, environment use, and welfare, whereas a-growth is Kaldor–Hicks efficient. Aversion to inequality for future generations makes a-growth and strong sustainability slightly feasible, with a reduction of welfare by 23 and 6% for OECD and non-OECD countries, respectively, for a-growth, and by 25 and 5% for strong sustainability, respectively. In addition, all solutions are Gini-equitable for consumption, environment use, and welfare.

5.2 Interior solutions

In this section, I search for feasible solutions arising from changes in all preference parameters related to a sense of concern or responsibility, for alternative values of the aversion to inequality parameters, by measuring feasibility in terms of acceptable welfare losses in OECD and non-OECD countries.

Figures 7, 8 and 9 show that there are no solutions for de-growth, whereas the other three sustainability paradigms have some solutions. Table 3 shows that weak sustainability

Table 2 Feasibility (green = feasible, yellow = moderately feasible, red = slightly feasible, white = unfeasible), and levels and percent changes in consumption (*X*), environment use (*E*), and welfare (*U*) for developed OECD countries (subscript N) and developing non-OECD countries (subscript S)

	CP		Responsibility for nature		Concern for future generations		Concern for non-OECD countries		Aversion to inequality for non-OECD countries		Aversion to inequality for future generations	
	Level	Change %	Level	Change %	Level	Change %	Level	Change %	Level	Change %	Level	Change %
WS												
X_N			17.50	−52								
E_N			1.15	−80								
U_N			1.86	−24								
X_S			5.64	−31								
E_S			1.82	−15								
U_S			1.00	−41								
AG												
X_N	*12.67*	−66	11.77	−68	*12.68*	−65	*13.79*	−62	29.90	−19	*12.50*	−66
E_N	*1.98*	−65	1.84	−68	*1.98*	−65	*2.16*	−62	4.67	−19	*1.95*	−66
U_N	*1.89*	−22	1.20	−51	***2.92***°	20	2.68	10	2.32	−5	*1.89*	−23
X_S	*6.28*	−24	6.40	−22	*6.28*	−24	*6.13*	−25	4.01	−51	*6.30*	−23
E_S	*1.64*	−23	1.67	−22	*1.64*	−23	*1.60*	−25	1.05	−51	*1.64*	−23
U_S	*1.58*	−6	1.10	−35	***2.44***°	44	1.57	−7	1.42	−16	*1.59*	−6
DG												
X_N	10.63	−71	4.91	−87	1.74	−95	2.31	−94	10.63	−71	10.63	−71
E_N	1.66	−71	0.77	−87	0.27	−95	0.36	−94	1.66	−71	1.66	−71
U_N	1.82	−26	1.82	−26	1.82	−26	1.82	−26	1.82	−26	1.82	−26
X_S	6.55	−20	7.30	−11	7.71	−6	7.64	−7	6.55	−20	6.55	−20
E_S	1.71	−20	1.90	−11	2.01	−6	1.99	−7	1.71	−20	1.71	−20
U_S	1.60	−5	1.03	−39	2.57	52	1.66	−2	1.60	−5	1.60	−5
SS												
X_N	*10.87*	−70	10.87	−70	*10.87*	−70	*10.87*	−70	*10.87*	−70	*10.87*	−70
E_N	*1.70*	−70	1.70	−70	*1.70*	−70	*1.70*	−70	*1.70*	−70	*1.70*	−70
U_N	*1.83*	−25	1.24	−49	***2.82***°	15	2.56	5	*1.83*	−25	*1.83*	−25
X_S	*6.51*	−21	6.51	−21	*6.51*	−21	*6.51*	−21	*6.51*	−21	*6.51*	−21
E_S	*1.70*	−21	1.70	−21	*1.70*	−21	*1.70*	−21	*1.70*	−21	*1.70*	−21
U_S	*1.60*	−5	1.09	−36	***2.46***°	46	1.60	−5	*1.60*	−5	*1.60*	−5

Efficiency (° = Pareto; underlined = Kaldor–Hicks) and equality (bold = MaxMin; italics = Gini). Current preferences (CP) = sustainability with today's preferences; responsibility for nature exists if $\beta_N = \beta_S = 0.73$; concern for future generations exists if $\gamma_N = \gamma_S = 0.73$; concern for non-OECD countries exists if $\delta_N = 0.73$; aversion to inequality for non-OECD countries exists if $\varepsilon = 0.99$; aversion to inequality for future generations exists if $\zeta = 0.99$. Sustainability paradigms: *WS* weak sustainability, *AG* a-growth, *DG* de-growth, *SS* strong sustainability

is slightly feasible with small (and moderate) aversion to inequality: solutions are Gini-equitable for consumption, environment use, and welfare and Kaldor–Hicks efficient and Gini-equitable for consumption and welfare. A-growth is slightly feasible with all levels of aversion to inequality, although the sustainability burden is larger for people of the non-OECD countries at larger values of ε and ζ; solutions are Gini-equitable for consumption, environment use, and welfare with small and moderate ε and ζ, and Kaldor–Hicks efficient with moderate and large ε and ζ. Strong sustainability is always slightly feasible, regardless of ε and ζ; all solutions are Gini-equitable for consumption, environment use, and welfare.

5.3 Sensitivity analyses

In this section, I search for feasible solutions at current preferences of OECD and non-OECD countries but in three different contexts: improved technology, decreased population, and modified consumption. Since the welfare of future generations is affected by all

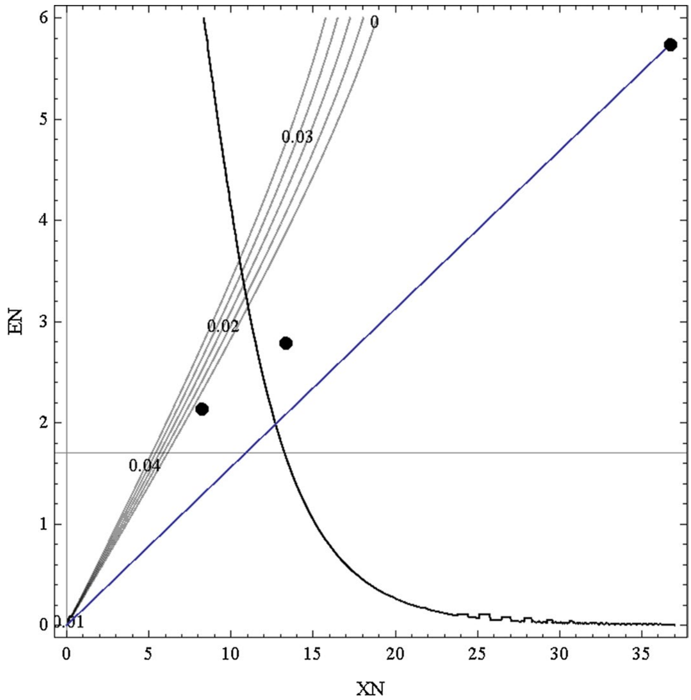

Fig. 7 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on all preference parameters related to a sense of concern or responsibility and small aversion to inequality: $\alpha_N = \beta_N = \gamma_N = \delta_N = 0.25$, $\alpha_S = \beta_S = \gamma_S = 0.\ 25$, $\varepsilon = \zeta = 0.01$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

three context changes, I have modified the reference values accordingly: $U_F = 1.81$ becomes $U_F = 1.95$, 1.92, and 1.56 in contexts with changes in technology (θ), population (η), and consumption (α), respectively, whereas $X_F = 10.876$ becomes $X_F = 14.502$ and 13.595 in contexts with changes in θ and η, respectively.

Figures 10, 11 and 12 show that there are no solutions for weak sustainability, whereas the other three sustainability paradigms always have solutions. Table 4 shows that improved technology makes a-growth, de-growth, and strong sustainability slightly feasible. In addition, the solutions are Kaldor–Hicks efficient; Gini-equitable for consumption, environment use, and welfare; and MaxMin-equitable for consumption and welfare. Decreased population makes a-growth, de-growth, and strong sustainability slightly feasible. In addition, the solutions are Kaldor–Hicks efficient and Gini-equitable for consumption, environment use, and welfare. Modified consumption makes a-growth slightly feasible and de-growth and strong sustainability moderately feasible. In addition, all solutions are Gini-equitable for consumption, environment use, and welfare.

In addition, feasible solutions can be found at current preferences and technology levels that characterise some representative OECD and non-OECD countries. I will refer to three highly populated countries in each group (i.e. Japan, Mexico, and the USA for OECD

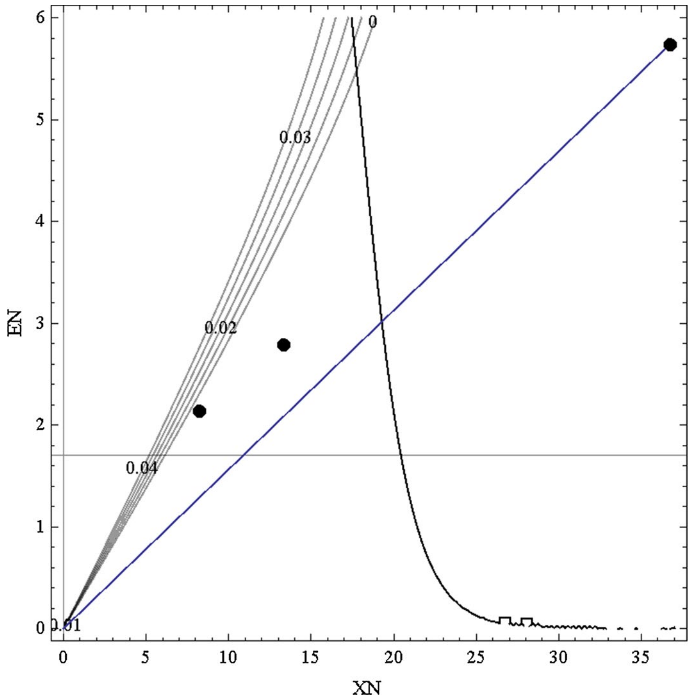

Fig. 8 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on all preference parameters related to a sense of concern or responsibility and medium aversion to inequality: $\alpha_N=\beta_N=\gamma_N=\delta_N=0.25$, $\alpha_S=\beta_S=\gamma_S=0.\ 25$, $\varepsilon=\zeta=0.50$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F-U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F\leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

countries; Brazil, India, and Russia for non-OECD countries). Table 5 shows that there are no solutions for WS, whereas the other three sustainability paradigms always have solutions. In particular, OECD countries could increase their welfare by 32, 18, and 15% if they all apply AG by using current preferences and technology levels that characterise the USA, Mexico and Japan, respectively. These results can be explained by comparing these OECD countries with the average representative OECD country in Sect. 5.2. Specifically, compared with the values for the representative OECD country, γ is larger and ζ is smaller in the USA; ε is smaller in Mexico; and θ is smaller, γ is larger, and ζ is smaller in Japan. However, non-OECD countries would be worse-off by 16, 15, and 15%, respectively. Note that DG and SS would decrease welfare for both the OECD and the non-OECD countries, although to different extents.

In contrast, the non-OECD countries could increase their welfare by 9% if they all apply AG based on the preferences and technology levels that characterise Brazil; they could instead increase their welfare by 15 and 6% if they all apply DG by using to the preferences and technology levels that characterise Brazil and India, respectively, and by 13 and 4% if they all apply SS based on the preferences and technology levels that characterise Brazil and India, respectively. These results can be explained by comparing these non-OECD

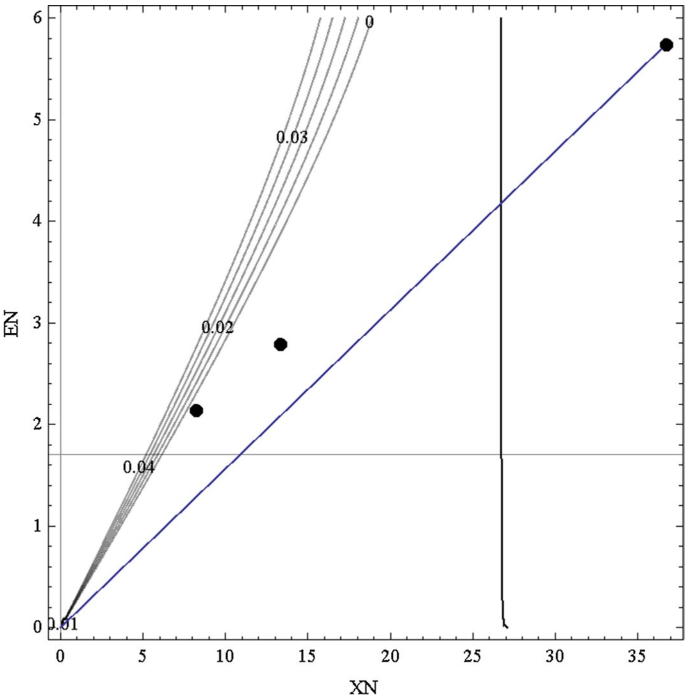

Fig. 9 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on all preference parameters related to a sense of concern or responsibility and large aversion to inequality: $\alpha_N = \beta_N = \gamma_N = \delta_N = 0.25$, $\alpha_S = \beta_S = \gamma_S = 0.\ 25$, $\varepsilon = \zeta = 0.99$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

countries with the average representative non-OECD country used in Sect. 5.2. Specifically, compared with the values for that representative non-OECD country, γ is larger and θ is smaller in Brazil, and ε is larger in India. However, OECD countries would be worse-off, with welfare decreasing by between 11 and 33%.

Note that the aversion to intra-generation inequality ε refers to comparisons between OECD versus non-OECD countries. Consequently, a smaller ε increases welfare in OECD countries, whereas a larger ε increases welfare in non-OECD countries. Moreover, the average strategies turned out to be less effective than country-specific strategies in 3 and 5 out of 9 scenarios for the OECD and non-OECD countries, respectively. Finally, the aversion to inter-generation inequality ζ refers to comparisons between current versus future generations. Consequently, a smaller ζ increases welfare in countries that are currently better-off than future generations, whereas a larger ζ increases welfare in countries that are currently worse-off than future generations.

Thus, R&D should be increased and technology levels should be improved (i.e. γ and θ) in both OECD countries (like Japan) and non-OECD countries (like Brazil). Unfortunately, all the countries I considered, including both OECD and non-OECD countries,

Table 3 Feasibility levels (yellow = moderately feasible, red = slightly feasible, white = unfeasible) and percent changes in consumption (X), environment use (E) and welfare (U) for developed OECD countries (subscript N) and developing non-OECD countries (subscript S)

	Small inequality aversion		Medium inequality aversion		Large inequality aversion	
	Level	Change (%)	Level	Change (%)	Level	Change (%)
WS						
X_N	*11.00*	−70	*17.50*	−52		
E_N	*3.15*	−45	5.40	−6		
U_N	*1.82*	−25	*2.03*	−17		
X_S	*6.50*	−21	*5.64*	−31		
E_S	*1.38*	−35	0.89	−59		
U_S	*1.60*	−5	*1.55*	−8		
AG						
X_N	*12.70*	−65	*19.27*	−48	26.70	−27
E_N	*1.99*	−65	*3.01*	−48	4.17	−27
U_N	*1.89*	−22	*2.09*	−14	2.26	−7
X_S	*6.27*	−24	*5.41*	−34	4.43	−46
E_S	*1.64*	−23	*1.41*	−34	1.16	−46
U_S	*1.58*	−6	*1.53*	−10	1.45	−14
SS						
X_N	*10.87*	−70	*10.87*	−70	*10.87*	−70
E_N	*1.70*	−70	*1.70*	−70	*1.70*	−70
U_N	*1.83*	−25	*1.83*	−25	*1.83*	−25
X_S	*6.51*	−21	*6.51*	−21	*6.51*	−21
E_S	*1.70*	−21	*1.70*	−21	*1.70*	−21
U_S	*1.60*	−5	*1.60*	−5	*1.60*	−5

Efficiency (underlined = Kaldor–Hicks) and equity (italics = Gini). Small, medium, and large aversions to inequality for non-OECD countries and future generations exist if $\varepsilon = \zeta = 0.01$, $\varepsilon = \zeta = 0.50$, and $\varepsilon = \zeta = 0.99$, respectively. Sustainability paradigms: *WS* weak sustainability, *AG* a-growth, *SS* strong sustainability. De-growth is not shown because there were no solutions (see Figs. 7, 8, 9)

were characterised by too small expenditures for environmental protection and foreign aid (i.e. β and δ) as a percentage of GDP to deduce any policy suggestion.

6 Discussion

From a *positive* perspective, the insights about sustainability paradigms and value changes can be summarised as follows (Table 6). By considering the effects of modified consumption, decreased population and improved technology, the ordering of sustainability paradigms is a-growth > strong sustainability > de-growth > weak sustainability. Note that de-growth is unfeasible if we disregard these effects. A sense of responsibility for nature β never produced a feasible solution, whereas the ordering of the other value changes was $\gamma > \delta > \varepsilon > \zeta$. Note that all senses of responsibility combined with medium inequality aversions were ranked II, like the effect of improved technology θ; all senses of responsibility combined with small or large inequality aversions were ranked III, like the effects of modified consumption α and decreased population η. Thus, $\gamma > \delta = (\beta, \gamma, \delta)$ if medium $(\varepsilon,\zeta) = \theta > \varepsilon = \alpha = \eta = (\beta, \gamma, \delta)$ if small $(\varepsilon,\zeta) = (\beta, \gamma, \delta)$ if large $(\varepsilon, \zeta) >$ current preferences $= \zeta$.

From a *normative* perspective, in terms of internal consistency, the insights about sustainability paradigms and value changes can be summarised as follows (Table 7). A case

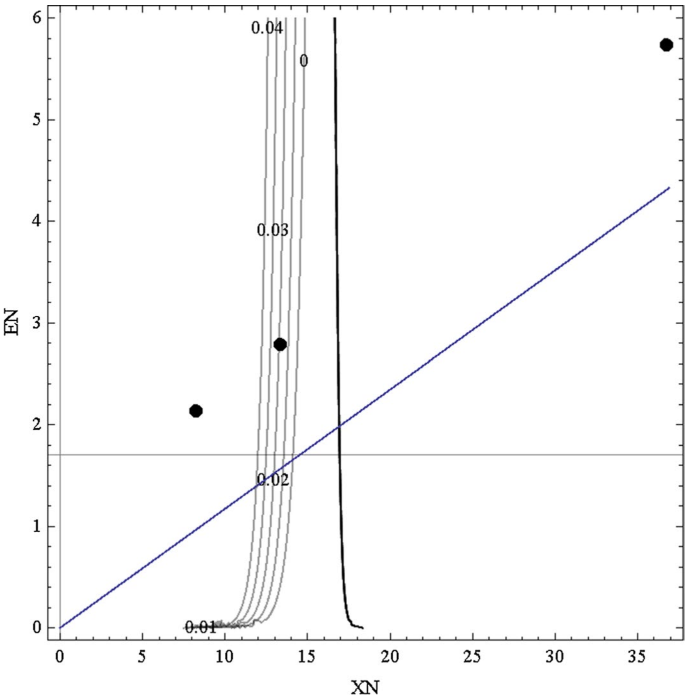

Fig. 10 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on improved technology (i.e. increased environmental efficiency, θ): $\alpha_N=\alpha_S=0.25$, $\beta_N=\gamma_N=\delta_N=0.01$, $\beta_S=\gamma_S=0.005$, $\varepsilon=\zeta=0.01$, $\eta=1.7$, $\theta_N=0.1172$, $\theta_S=0.1957$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F-U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

consistent with weak sustainability (i.e. Kaldor–Hicks efficient with small ε and ζ) has no solutions. A case consistent with a-growth (i.e. Gini-equitable for welfare with small ε and ζ) allows a choice between γ, δ, all senses of responsibility combined, and all context changes, although γ is more feasible. A case consistent with de-growth (i.e. MaxMin-equitable for welfare for any ε and ζ) must rely on context changes. A case consistent with strong sustainability (i.e. Gini-equitable for consumption and environment use for any ε and ζ) allows a choice between γ, ε, and ζ, all senses of responsibility combined, and all context changes, although γ is more feasible. In summary, by considering the effects of modified consumption, decreased population, and improved technology, the ordering of sustainability paradigms is strong sustainability > a-growth > de-growth, whereas weak sustainability was never internally consistent. Note that de-growth is internally inconsistent if we disregard these effects. Although modified consumption, decreased population, and improved technology are ranked better than a sense of responsibility for future generations (i.e. $\alpha=\eta=\theta>\gamma$), the ordering of the value changes is $\gamma=(\beta, \gamma, \delta)$ with all $(\varepsilon, \zeta)>\delta=\varepsilon=\zeta$.

From a *normative* perspective, in terms of consistency with equity approaches, the insights about sustainability paradigms and value changes can be summarised as follows (Table 8). A case consistent with the utilitarian approach (here, Harsanyi; Kaldor–Hicks

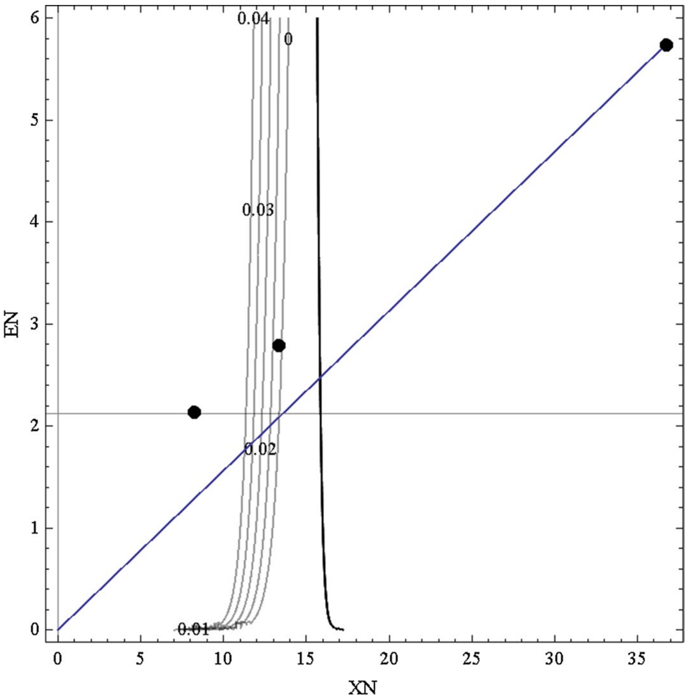

Fig. 11 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on reduced world population (η): $\alpha_N = \alpha_S = 0.25$, $\beta_N = \gamma_N = \delta_N = 0.01$, $\beta_S = \gamma_S = 0.005$, $\varepsilon = \zeta = 0.01$, $\eta = 2.125$, $\theta_N = 0.1563$, $\theta_S = 0.2610$. Numerical values on each curve represent $(U_F - UC)/U_F$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

efficient with small ε and ζ) could be a-growth with a change in γ or δ, or strong sustainability with a change in γ or δ.

With a focus on consumption or environment (here, Dworkin; Gini-equitable for consumption or environment use), a case consistent with the egalitarian approach could be weak sustainability with all senses of responsibility combined and small or medium aversion to inequality; it could be a-growth with current preferences, a change in γ, δ, or ζ, all preference parameters related to a sense of concern or responsibility with small or medium aversion to inequality, and all context changes; it could be de-growth with all context changes; or it could be strong sustainability with current preferences, a change in γ, δ, ε, or ζ, all preference parameters related to a sense of concern or responsibility with all aversion to inequality, and all context changes.

With a focus on welfare (here, Arneson; Gini-equitable in welfare), a case consistent with the egalitarian approach could be weak sustainability with all preference parameters related to a sense of concern or responsibility and small or medium aversion to inequality; it could be a-growth with current preferences, a change in γ or ζ, all preference parameters related to a sense of concern or responsibility with all levels of aversion, and all context changes; it could be de-growth with context changes; it could be strong sustainability with

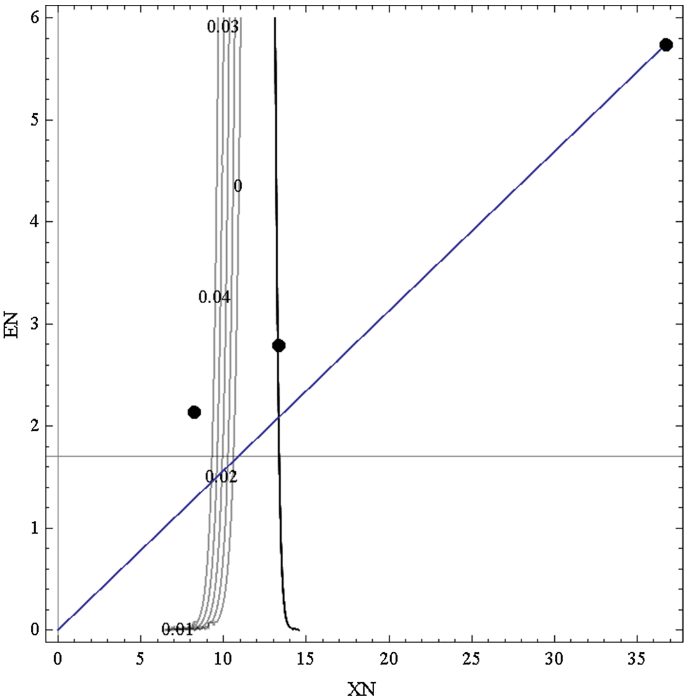

Fig. 12 Solutions for use of the environment (E_N) as a function of per capita consumption (X_N) for OECD countries based on changed consumption preferences (α): $\alpha_N = \alpha_S = 0.1875$, $\beta_N = \gamma_N = \delta_N = 0.01$, $\beta_S = \gamma_S = 0.005$, $\varepsilon = \zeta = 0.01$, $\eta = 1.7$, $\theta_N = 0.1563$, $\theta_S = 0.2610$. The cluster of curves represents the relationship between E_N and X_N for four values of $(U_F - U_C)/U_F$, with the value decreasing from left to right. The thick decreasing curve represents the first-order conditions for Max U. The increasing straight line represents the border condition for $E_F \leq E_C$. The horizontal straight line represents the first-order conditions for Max W. The highest, middle, and lowest dots are the representative OECD, world, and non-OECD individuals, respectively

current preferences, a change in γ, ε, or ζ, all preference parameters related to a sense of concern or responsibility with all levels of aversion, and all context changes.

With a focus on consumption and environment (here, Sen; Gini-equitable in consumption and environment use), a case consistent with the egalitarian approach could be weak sustainability with all preference parameters related to a sense of concern or responsibility and small aversion to inequality; could be a-growth with current preferences, a change in γ, δ, or ζ, all preference parameters related to a sense of concern or responsibility with small or medium aversion, and all context changes; could be de-growth with context changes; or could be strong sustainability with current preferences, a change in γ, δ, ε, or ζ, and all preference parameters related to a sense of concern or responsibility, with all levels of aversion, for all context changes.

A case consistent with the contractarian approach (here, Rawls; MaxMin-equitable in consumption, environment use, or welfare) could be a-growth with a change in γ, improved technology, and modified consumption; could be de-growth with improved technology and modified consumption; or could be strong sustainability with a change in γ, improved technology, and modified consumption. In summary, by considering the effects of modified consumption, decreased population, and improved technology,

Table 4 Feasibility levels (green = feasible, yellow = moderately feasible, red = slightly feasible, white = unfeasible), and percent changes in consumption (*X*), environment use (*E*) and welfare (*U*) for developed OECD countries (subscript N) and developing non-OECD countries (subscript S)

	Improved technology		Decreased population		Modified consumption	
	Level	Change (%)	Level	Change(%)	Level	Change(%)
AG						
X_N	***16.91***	− 54	*15.83*	− 57	*13.32*	− 64
E_N	1.98	− 65	*2.47*	− 57	*2.08*	− 64
U_N	***2.04***	− 16	*2.00*	− 18	***2.26***	− 7
X_S	***8.37***	2	*7.85*	− 4	*6.19*	− 25
E_S	1.64	− 23	*2.05*	− 4	*1.62*	− 24
U_S	***1.70***	1	*1.67*	− 1	***1.77***	5
DG						
X_N	***14.09***	− 62	*13.35*	− 64	*10.59*	− 71
E_N	*1.65*	− 71	*2.09*	− 64	*1.66*	− 71
U_N	***1.95***	− 20	*1.92*	− 21	***2.11***	− 14
X_S	***8.74***	6	*8.17*	− 1	*6.55*	− 20
E_S	*1.71*	− 20	*2.13*	0	*1.71*	− 20
U_S	***1.72***	2	*1.69*	0	***1.80***	7
SS						
X_N	***14.50***	− 61	*13.59*	− 63	*10.87*	− 70
E_N	*1.70*	− 70	*2.12*	− 63	*1.70*	− 70
U_N	***1.96***	− 19	*1.93*	− 21	***2.12***	− 13
X_S	***8.68***	6	*8.14*	− 1	*6.51*	− 21
E_S	*1.70*	− 21	*2.13*	− 1	*1.70*	− 21
U_S	***1.72***	2	*1.69*	0	***1.80***	6

Efficiency (underlined = Kaldor–Hicks) and equality (bold = MaxMin; italic = Gini). Improved technology exists if $\theta_N = 0.1172$ and $\theta_S = 0.1957$; decreased population exists if $\eta = 2.125$; modified consumption exists if $\alpha_N = \alpha_S = 0.1875$. Sustainability paradigms: *AG* a-growth, *DG* de-growth, *SS* strong sustainability. Weak sustainability is not shown because there were no feasible solutions (see Figs. 10, 11, 12)

the ordering of sustainability paradigms is strong sustainability > a-growth > de-growth > weak sustainability. Note that de-growth is inconsistent with any equity approach if we disregard these effects. Although modified consumption and improved technology are ranked better than a sense of responsibility for future generations (i.e. $\alpha = \theta > \gamma > (\beta, \gamma, \delta)$ with all $(\varepsilon, \zeta) = \eta > \delta = \zeta =$ current preferences $> \varepsilon$), the ordering of value changes is $\gamma > \delta = \zeta > \varepsilon$.

The approach developed in this paper confirms several expected (i.e. intuitive) insights:

1. An inter-generational sense of responsibility (γ) is the most important feature, although a concern for non-OECD countries (δ) also leads to sustainability with a-growth and strong sustainability.
2. A population reduction makes de-growth feasible.
3. Improved technology makes a-growth more feasible, and to a greater extent than with a population reduction.
4. Modified consumption makes de-growth more feasible.
5. Strong sustainability reduces inequality in consumption, environment use, and welfare in all scenarios, apart from welfare in a case with a concern for non-OECD countries (δ).

Table 5 Alternative feasible solutions if OECD and non-OECD countries use the preferences and technology levels that characterise Japan, Mexico, and the USA (JAP, MEX, and USA, respectively) for OECD countries, and Brazil, India, and Russia (BRA, IND, and RUS, respectively) for non-OECD countries

	Levels						Changes (%)					
	JAP	MEX	USA	BRA	IND	RUS	JAP	MEX	USA	BRA	IND	RUS
AG												
X_N	31.158	24.781	29.428	16.784	21.544	22.741	−15	−33	−20	−54	−41	−38
E_N	4.453	4.454	4.774	2.623	3.367	3.554	−22	−22	−17	−54	−41	−38
U_N	2.825	2.895	3.229	2.029	2.152	2.179	**15**	**18**	**32**	−17	−12	−11
X_S	4.198	4.197	3.928	7.231	5.404	5.285	−49	−49	−52	−12	−34	−36
E_S	1.096	1.096	1.025	1.497	1.334	1.293	−49	−49	−52	−30	−38	−40
U_S	1.436	1.436	1.413	1.841	1.639	1.538	−15	−15	−16	**9**	−3	−9
DG												
X_N	6.639	6.834	6.614	8.270	7.089	7.167	−82	−81	−82	−77	−81	−80
E_N	1.566	1.681	1.591	1.650	1.656	1.660	−73	−71	−72	−71	−71	−71
U_N	1.791	1.892	1.944	1.709	1.643	1.646	−27	−23	−21	−30	−33	−33
X_S	7.145	6.910	7.041	8.642	7.413	7.469	−13	−16	−14	5	−10	−9
E_S	1.729	1.704	1.724	1.711	1.710	1.709	−19	−20	−19	−20	−20	−20
U_S	1.636	1.623	1.631	1.943	1.796	1.680	−3	−4	−4	**15**	**6**	−1
SS												
X_N	11.895	9.459	10.479	10.876	10.876	10.876	−68	−74	−71	−70	−70	−70
E_N	1.700	1.700	1.700	1.700	1.700	1.700	−70	−70	−70	−70	−70	−70
U_N	2.127	2.107	2.273	1.829	1.827	1.826	−13	−14	−7	−25	−25	−25
X_S	6.514	6.513	6.514	8.210	6.886	6.949	−21	−21	−21	0	−16	−15
E_S	1.700	1.700	1.700	1.700	1.700	1.700	−21	−21	−21	−21	−21	−21
U_S	1.599	1.599	1.600	1.913	1.759	1.650	−5	−5	−5	**13**	**4**	−2

Bold values indicate positive changes in welfare (U) for developed OECD countries (subscript N) or developing non-OECD countries (subscript S)

The approach developed in this paper provides several unexpected (i.e. counterintuitive) insights:

1. Aversion to inequality for non-OECD countries (ε) is more important than aversion to inequality for future generations (ζ), although people of non-OECD countries pay more with larger ε than with larger ζ, whereas the opposite holds for people in OECD countries.
2. An increase in aversion to inequality for either non-OECD countries (ε) or for future generations (ζ) makes a-growth more feasible in cases with a sense of responsibility for nature (β) and current (δ) and future (γ) generations.
3. Modified consumption makes strong sustainability more feasible.
4. In a case with a sense of responsibility for both nature (β) and current (δ) and future (γ) generations, a-growth and strong sustainability lead to feasible sustainability conditions that provide similar welfare for OECD and non-OECD countries, despite differences in the representative individuals, if aversion to inequality both for non-OECD countries (ε) and for future generations (ζ) is small.
5. A large sense of responsibility for nature (β) provides no feasible solutions for all sustainability paradigms.

Table 6 Feasibility of the sustainability paradigms

	CP	β	γ	δ	ε	ζ	β, γ, δ with small ε, ζ	β, γ, δ with medium ε, ζ	β, γ, δ with large ε, ζ	α	η	θ	Rank with α, η, θ	Rank without α, η, θ
WS							Sli	Sli					IV	III
AG	Sli		Fea	Mod	Mod	Sli	Sli	Mod	Mod	Sli	Sli	Mod	I	I
DG										Sli	Sli	Sli	III	
SS	Sli		Fea	Mod	Sli	Sli	Sli	Sli	Sli	Sli	Sli	Sli	II	II
Rank			I	II	III	IV	III	II	III	III	III	II		

CP current preferences, *Fea* feasible, *Mod* moderately feasible, *Sli* slightly feasible, *blank* unfeasible. Sustainability paradigms: *WS* weak sustainability, *AG* a-growth, *DG* de-growth, *SS* strong sustainability

Table 7 Internal consistency

	CP	β	γ	δ	ε	ζ	β, γ, δ with small ε,ζ	β, γ, δ with medium ε,ζ	β, γ, δ with large ε,ζ	α	η	θ	Rank with α, η, θ	Rank without α, η, θ
WS													IV	
AG			Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes	II	II
DG										Yes	Yes	Yes	III	
SS			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	I	I
Rank			II	III	IV	IV	II	II	II	I	I	I		

Yes = internally consistent, blank = internally inconsistent. *CP* current preferences. Sustainability paradigms: *WS* weak sustainability, *AG* a-growth, *DG* de-growth, *SS* strong sustainability

Table 8 Consistency with the equity approaches

	CP, ζ	β	γ	δ	ε	β, γ, δ with all ε, ζ	α, θ	η	Rank with α, η, θ	Rank without α, η, θ
WS						Dw-Ar-Se			IV	III
AG	Dw-Ar-Se		All	Ut-Dw-Se		Dw-Ar-Se	Dw-Ar-Se-Co	Dw-Ar-Se	II	II
DG							Dw-Ar-Se-Co	Dw-Ar-Se	III	
SS	Dw-Ar-Se		All	Ut-Dw-Se	Dw-Ar-Se	Dw-Ar-Se	Dw-Ar-Se-Co	Dw-Ar-Se	I	I
Rank	IV		II	IV	V	II	I	III		

Ut utilitarian approach, *Dw* Dworkin egalitarian approach, *Ar* Arneson egalitarian approach, *Se* Sen egalitarian approach, *Co* contractarian approach, *All* all equity approaches, blank = inconsistent with any equity approach. Sustainability paradigms: *WS* weak sustainability, *AG* a-growth, *DG* de-growth, *SS* strong sustainability

Weaknesses of the present study include:

- Environmental free-riding (i.e. some individuals pay for the consequences of the environmental use by other individuals) is not modelled (e.g. in Appendix 2, E_N and E_S are replaced by $E_C = \sum p_i E_i$). However, welfare in OECD countries depends on welfare in non-OECD countries, which in turn depends on their environmental use (i.e. U_N depends on U_S, which depends on $E_S = 2\eta - E_N$ and $E_S = \eta/p_S - (p_N/p_S) E_N$ for non-weighted and weighted sustainability conditions, respectively).
- The institutionalisation of sustainability (i.e. implementation of technical, legal, and moral systems; development of organisations, boards, and offices to implement sustainability strategies; Ott 2014) is not discussed. However, most operational conditions that would lead towards sustainability are identified (e.g. δ should be preferred to γ).
- Feasibility was defined based on arbitrary thresholds (i.e. a welfare reduction larger than 25% was defined as unfeasible). However, comparisons between value changes and the four sustainability paradigms are independent of these thresholds (e.g. a-growth and strong sustainability should be preferred to weak sustainability, which should be preferred to de-growth).

Strengths of the present study include:

- The framework combines sustainability paradigms and equity approaches to find a theoretically coherent solution that can lead to sustainability or an operationally implementable policy that will lead to sustainability.
- The results confirm insights in the literature on context changes such as modified consumption and improved technology (Zagonari 2015), but they also expand these insights to include value changes by distinguishing among four sustainability paradigms and by considering proportions of the global population in OECD and non-OECD countries and the dynamics of these populations.
- Neither a top-down nor a bottom-up approach to preference changes is suggested; instead, the most important features linked to each sustainability paradigm and equity approach are identified.

Therefore, in *normative* terms, if the a priori commitment is a consistent sustainability paradigm, this study suggests a focus on γ (if a-growth or strong sustainability is adopted), δ (if a-growth is adopted), ε (if strong sustainability is adopted), ζ (if strong sustainability is adopted), all senses of concern or responsibility combined (if a-growth or strong sustainability is adopted), and all context changes (if a-growth, de-growth, or strong sustainability is adopted). Moreover, in *normative* terms, if the a priori commitment is a consistent equity approach, this paper suggests a focus on γ (in the case of utilitarian, egalitarian, or contractarian approaches), δ (in the case of utilitarian or egalitarian approaches), ε (in the case of an egalitarian approach), and ζ (in the case of an egalitarian approach). Finally, in *positive* terms, the most effective sustainability conditions, regardless of consistency of the adopted paradigm or approach, appear to be $\gamma > \delta > \varepsilon > \zeta$ for value changes and a-growth > strong sustainability > de-growth > weak sustainability for sustainability paradigms.

7 Conclusions

Three main novel findings were obtained in this study. First, weak sustainability and de-growth, which include the constraint $U_F \geq U_C$, are both theoretically problematic to sustain and empirically difficult to implement, since the happiness or needs of future generations, which depend on spatial and temporal variations in culture, cannot be easily defined or measured. Second, sustainability conditions cannot be achieved by relying only on a sense of responsibility for nature, but instead must rely on a concern for both future generations and non-OECD countries. In other words, relying on a sense of responsibility for nature, which only indirectly affects future generations, is theoretically ineffective; indeed, welfare losses in the absence of concern for future generations and non-OECD countries are large under all paradigms, although sustainability conditions differ among the paradigms. Relying on a sense of responsibility for nature is also operationally difficult; for example, agreements between religions are difficult to achieve, since their philosophies have evolved from different cultural backgrounds and histories. Third, the perspectives of a single individual (i.e. the focus is on individual sustainability) and of a representative individual (i.e. the focus is on overall sustainability) that are assumed by a-growth and strong sustainability, respectively, lead to sustainability at similar levels of per capita consumption and use of the environment by both OECD and non-OECD countries.

The main *theoretical* good news from this study is that the ecological debt (i.e. the current average ecological footprint of 2.79 ha is larger than the long-run equilibrium value of 1.7 ha) can be paid in full by the current generation if there is significant concern for future generations and non-OECD countries, although the welfare burden depends on the possible preference changes and the distribution of this burden depends on the adopted sustainability paradigms.

The main *operational* good news is threefold. First, sustainability can be achieved at current preferences with reasonable burdens for the current generations in OECD and non-OECD countries if a-growth or strong sustainability is adopted. Second, improved technology and modified consumption could increase welfare for the current non-OECD generation compared with the status quo. Third, whenever a feasible solution exists, the sustainability burden on current OECD generations is proportionally larger than that on current non-OECD generations.

The main *theoretical* bad news is that two of the four sustainability paradigms are not internally consistent: weak sustainability was never Kaldor–Hicks efficient (with and without context changes), whereas de-growth was never MaxMin-equitable (without context changes).

The main *operational* bad news is threefold. First, achieving sustainability implies an increase in inter-generational inequality: the current unsustainable representative individual for the world is closer to the future sustainable representative individual than to the current sustainable representative individual in terms of both consumption and environment use in all sustainability paradigms. Second, reducing the world's population, as endorsed by the de-growth paradigm, is not enough to achieve sustainability, although the current non-OECD generation would not decrease its status quo welfare if strong sustainability or de-growth were adopted. Third, if the suggested changes in preferences related to a sense of concern or responsibility are interpreted as changes in the budget share, sustainability conditions appear difficult to achieve.

Three main developments from this paper seem to be particularly promising. First, it should be possible to move from aggregated data to more detailed data on consumption levels. This would allow the inclusion of expenditures for additional factors such as health and education, possibly at a national level. Second, it should be possible to enhance the current one-shot model to produce a dynamic model, which would allow an investigation of issues related to overlapping generations. Third, moving from aggregated data to more detailed data on the direct and indirect use of Earth's resources would allow the framework to account for both pollution production and resource use, possibly at a national level.

Appendix 1: List of variable names

α_F: the future preference for consumption
α_N: the preference for consumption in OECD countries
α_S: the preference for consumption in non-OECD countries
β_N: the degree of concern for nature in OECD countries
β_S: the degree of concern for nature in non-OECD countries
γ_N: the degree of concern for future generations in OECD countries
γ_S: the degree of concern for future generations in non-OECD countries
δ_N: the degree of concern for the current non-OECD generation in OECD countries
ε: the degree of aversion to intra-generational inequality
ζ: the degree of aversion to inter-generational inequality
η: per capita equilibrium use of the environment consistent with the current world population
θ_N: the use of the environment for each consumption unit for the OECD current generation
θ_S: the use of the environment for each consumption unit for the non-OECD current generation
θ_F: the use of the environment for each consumption unit for the future generation
E_C: population-weighted per capita use of the environment by the current generation
E_F: per capita use of the environment by the future generation
E_N: per capita use of the environment in the current OECD generation
E_S: per capita use of the environment in the current non-OECD generation
p_N: proportion of the global population in the OECD countries
p_S: proportion of the global population in the non-OECD countries
U: overall utility as dependent on consumption
U_C: population-weighted utility for the current generation as dependent on consumption
U_F: utility for the future generations as dependent on consumption
U_N: utility for the current OECD generation as dependent on consumption
U_S: utility for the current non-OECD generation as dependent on consumption
W: overall welfare as dependent on environment use
W_C: population-weighted welfare of the current generation as dependent on environment use
X_C: population-weighted per capita consumption in the current generation
X_F: per capita consumption in the future generation
X_N: per capita consumption in the OECD current generation
X_S: per capita consumption in the non-OECD current generation

Appendix 2: Use of a shared common environment

In the case of n countries at a similar development level, and which share a common environment (e.g. a closed sea), the model changes as follows:

$$U_{\mathrm{F}} = \mathrm{X}_{\mathrm{F}}^{\alpha_{\mathrm{F}}} \text{ with } \alpha_{\mathrm{F}} = \frac{1}{n}\sum_{i}^{n}\alpha_i \quad \text{and} \quad X_{\mathrm{F}} = \eta/\theta_{\mathrm{F}} \text{ with } \theta_{\mathrm{F}} = \frac{1}{n}\sum_{i}^{n}\theta_i$$

$$U_{C_i} = X_i^{\alpha_i}\left(\sum p_i E_i\right)^{-\beta_i} U_{\mathrm{F}}^{\gamma_i}\left(\sum p_j U_{\mathrm{C}_j}\right)^{\delta_i}$$

$$U_{\mathrm{C}} = \left[\left(\sum p_i U_{\mathrm{C}_i}\right)^{1-\varepsilon}\right]^{1/(1-\varepsilon)}$$

$$U = \left[U_{\mathrm{C}}^{1-\zeta} + U_{\mathrm{F}}^{1-\zeta}\right]^{1/(1-\zeta)}$$

$$W_{\mathrm{C}} = \left[\left(\sum p_i E_i\right)^{1-\varepsilon}\right]^{1/(1-\varepsilon)}$$

$$W = \left[E_{\mathrm{C}}^{1-\zeta} + E_{\mathrm{F}}^{1-\zeta}\right]^{1/(1-\zeta)}$$

where i refers to a sum which includes all n countries, whereas j refers to a sum that excludes country i. Note that this system of equations could be solved for X_i to check for the existence of a sustainability solution at current preferences. Alternatively, it could be solved for a set of consumption preferences (i.e. α_i, β_i, γ_i, δ_i, ε, ζ) at current consumption levels to check which country should change its preferences to a greater extent. Moreover, $U_{\mathrm{F}} \geq U_i$ could be used instead of $U_{\mathrm{F}} \geq U_{\mathrm{C}}$. Finally, the model could be solved in a cooperative context, in which δ_i could be positive. Alternatively, it could be solved in a non-cooperative context, in which δ_i is set to 0.

Appendix 3: Statistical analysis for the environmental ethics

In this section, I will estimate the significance and size of the five main secular environmental ethics for sustainability (i.e. responsibility for nature β, for future generations γ, and for the current generation in developing countries δ; aversion to inequality for the current generation ε and for future generations ζ). To do so, I will rely on the same dataset discussed in Sect. 4 (i.e. 145 countries) and the formulas introduced in Sect. 3. The additional data used in this analysis are presented in Table S1 of the Supplementary Materials II. In particular, formulas involving the parameters α, β, γ, and δ suggest the need to use a logarithmic transformation of the dependent variables (i.e. ln U_{N} and ln U_{S} for OECD and non-OECD countries, respectively) and independent variables (i.e. ln $\mathrm{GDP}_{\mathrm{S}}$, ln EF_{S}, and ln U_{F} for non-OECD countries, and ln $\mathrm{GDP}_{\mathrm{N}}$, ln EF_{N}, ln U_{S}, and ln U_{F} for OECD countries), and then to estimate the two equations linear model for ln U_N and ln U_S using a three-stage least-squares regression. Note that all parameters are assumed to be positive. In summary, I will estimate the following two equations:

$$\ln U_S = \alpha_S \ln \mathrm{GDP}_S - \beta_S \ln \mathrm{EF}_S + \gamma_S \ln U_F + \xi_S$$

And

$$\ln U_N = \alpha_N \ln \mathrm{GDP}_N - \beta_N \ln \mathrm{EF}_N + \gamma_N \ln U_F + \delta_N \ln U_S + \xi_N$$

where ξ_S and ξ_N are the estimation residuals. Note that I estimated ln U_S and ln U_N by using the consumption expenditures as a percentage of GDP as a proxy for α, the environmental protection expenditures as a percentage of GDP as a proxy for β, the R&D expenditures as a percentage of GDP as a proxy for γ, and the foreign aid expenditures as a percentage of GDP as a proxy for δ. Moreover, I estimated U_F by using world average values for α. Finally, I expect a positive sign for all parameters apart from those attached to ln E_F. Estimation results are presented in Table 9.

Thus, the parameters either have the expected sign (i.e. responsibility to nature β and for future generations γ, with $\beta_N \approx \beta_S$ and $\gamma_N \approx \gamma_S$, as well as for α, with $\alpha_N \approx \alpha_S$) or are non-significant (i.e. responsibility for the current generation in developing countries δ_N).

Next, the formulas involving parameters ε and ζ suggest the need to use a logarithmic transformation of the independent variable (i.e. ln U) and then to estimate a nonlinear equation by applying nonlinear least-squares regression to the fitted values obtained from the previous regressions. Note that I estimated ln U (the overall utility) by using $1 -$ the Gini coefficient as a proxy for ε, and $1 -$ the government debt as a percentage of GDP as a proxy for ζ, with these coefficients constrained in [0, 1]. That is, if the observed government debt as a percentage of GDP is larger than 100%, ζ is assumed to be 0. Moreover, I performed the estimation by using 1–ε and 1–ζ. Finally, both ε and ζ are assumed to be constrained in [0, 1]. In summary, I will estimate the following equation:

$$\ln U = \frac{1}{1-\zeta} \ln\left\{ \left[\left(0.18 U_N\right)^{1-\varepsilon} + \left(0.82 U_S\right)^{1-\varepsilon} \right]^{1-\zeta/1-\varepsilon} + U_F^{1-\zeta} \right\} + \psi$$

Table 9 Impacts of the environmental ethics parameters on welfare: β_N and β_S are attached to lnefn and lnefs, respectively; γ_N and γ_S are attached to lnuf in the first and second estimations, respectively; and δ_N is attached to lnus in the first estimation

Equation	Obs	Parms	RMSE	"R-sq"	chi2	P
lnun	145	4	.1839727	0.9826	8114.39	0.0000
lnus	145	3	.6154106	0.9455	2516.86	0.0000
	Coef.	Std. err.	z	$P>\|z\|$	[95% Conf. Interval]	
lnun						
lngdpn	.3803631	.0491099	7.75	0.000	.2841094	.4766168
lnefn	−.6815392	.114471	−5.95	0.000	−.9058981	−.4571802
lnuf	.0231337	.1328495	0.17	0.862	−.2372466	.2835141
lnus	−.0249262	.1445152	−0.17	0.863	−.3081708	.2583184
lnus						
lngdps	.3837903	.0174606	21.98	0.000	.3495681	.4180125
lnefs	−.6924374	.1074255	−6.45	0.000	−.9029875	−.4818874
lnuf	.0167824	.0333154	0.50	0.614	−.0485145	.0820794

Table 10 Impacts of the environmental ethics parameters on welfare: aversion to inequality for current generations ε and future generations ζ, with ep = 1 − ε, and ze = 1 − ζ

Source	SS	*df*	MS	
Model	2590.08645	2	1295.04322	Number of obs = 145
Residual	775.464861	143	5.42283119	R-squared = 0.7696
Total	3365.55131	145	23.2106987	Adj R-squared = 0.7664
				Root MSE = 2.328697
				Res. dev. = 654.6179

lnuee	Coef.	Std. err.	*t*	*P* > |*t*|	[95% Conf. Interval]	
ze	.2870542	.0307511	9.33	0.000	.2262686	.3478397
ep	13.61995	2.73e+09	0.00	1.000	− 5.39e+09	5.39e+09

where ψ is the estimation residual, and 0.18 and 0.82 are the proportions of the world's population in OECD and non-OECD countries, respectively, in 2012. Note that I expect a positive sign for all parameters. Estimation results are presented in Table 10.

Thus, the estimated concern for the current generation is negative but non-significant (i.e. $\varepsilon = -13.619 + 1$), whereas the estimated concern for future generations is in (0,1) and significant (i.e. $\zeta = -0.287 + 1$).

In summary, the reliability (i.e. significance and size) rankings in the statistical results are intuitive for sustainability (i.e. $\zeta > \beta > \gamma > \delta > \varepsilon$). However, combining this reliability ranking with the feasibility ranking obtained in the numerical simulations (i.e. $\gamma > \delta > \varepsilon > \zeta > \beta$) leads to a pessimistic conclusion about sustainability: the most reliable factors (i.e. $\zeta > \beta$) are unfeasible, whereas the most feasible factors (i.e. $\gamma > \delta$) are unreliable to achieve sustainability.

References

Arneson, R. J. (1989). Equality and equal opportunity for welfare. *Philosophical Studies, 56,* 77–93.

Asheim, G. B., Mitra, T., & Tungodden, B. (2012). Sustainable recursive social welfare functions. *Economic Theory, 49,* 267–292.

Aznar-Marquez, J., & Ruiz-Tamarit, J. R. (2016). Environmental pollution, sustained growth, and sufficient conditions for sustainable development. *Economic Modelling, 54,* 439–449.

Caselles, A. (2013). An application of fuzzy cognitive maps to improve well-being, sustainability and the globalization process. *Systems Research and Behavioural Science, 30,* 646–660.

Dworkin, R. (1981). What is equality? Part 2: Equality of resources. *Philosophy & Public Affairs, 10,* 283–345.

Golub, A., Mahoney, M., & Harlow, J. (2013). Sustainability and intergenerational equity: Do past injustices matter? *Sustainability Science, 8,* 269–277.

Gosseries, A. (2008). On future generations' future rights. *Journal of Political Philosophy, 16,* 446–474.

Habib, A. (2013). Sharing the Earth: Sustainability and the currency of inter-generational environmental justice. *Environmental Values, 22,* 751–764.

Harsanyi, J. C. (1982). Morality and the theory of rational behaviour. In A. Sen & B. Williams (Eds.), *Utilitarianism and beyond* (pp. 39–62). Cambridge: Cambridge University Press.

Jain, P., & Jain, P. (2013). Sustainability assessment index: A strong sustainability approach to measure sustainable human development. *International Journal of Sustainable Development and World Ecology, 20,* 116–122.

Kallis, G. (2011). In defence of de-growth. *Ecological Economics, 70,* 873–880.

Kallis, G., Kerschner, C., & Martinez-Alier, J. (2012). The economics of de-growth. *Ecological Economics, 84,* 172–180.

Kershnar, S., & Purves, D. (2016). A new argument for the irrelevance of equality for intrinsic value. *Philosophia (United States), 45,* 277–297.
Kopnina, H. (2016). The victims of unsustainability: A challenge to sustainable development goals. *International Journal of Sustainable Development and World Ecology, 23,* 113–121.
Koukouzelis, K. (2012). Sustainable development, liberty, and global social justice. *Public Reason, 4,* 165–181.
Lauwers, L. (2012). Intergenerational equity, efficiency, and constructability. *Economic Theory, 49,* 227–242.
Lomasky, L. (1987). *Persons, rights, and the moral community*. New York: Oxford University Press.
Norton, B. G. (2005). *Sustainability: A philosophy of adaptive ecosystem management*. Chicago: University of Chicago Press.
Nozick, R. (1974). *Anarchy, state, and Utopia*. New York: Basic Books.
Ott, K. (2014). Institutionalising strong sustainability: A Rawlsian perspective. *Sustainability (Switzerland), 6,* 894–912.
Pedersen, K. P. (2015). Religious ethics and the environment: A review essay. *Journal of Religious Ethics, 43,* 558–585.
Rawls, J. (1971). *A theory of justice*. Cambridge: Harvard University Press.
Salas-Zapata, W. A., Rios-Osorio, L. A., & Mejia-Escobar, J. A. (2017). Social-ecological resilience and the quest for sustainability as object of science. *Environment, Development and Sustainability, 19*(6), 2237–2252.
Saniotis, A. (2012). Muslims and ecology: Fostering Islamic environmental ethics. *Contemporary Islam, 6,* 155–171.
Schlör, H., Fischer, W., & Hake, J. F. (2015). The system boundaries of sustainability. *Journal of Cleaner Production, 88,* 52–60.
Sen, A. K. (1993). Capability and well-being. In M. C. Nussbaum & A. K. Sen (Eds.), *The quality of life* (pp. 30–53). Oxford: Clarendon Press.
Van den Bergh, J. C. J. M. (2010). Externality or sustainability economics? *Ecological Economics, 69,* 2047–2052.
Van den Bergh, J. C. J. M. (2011). Environment versus growth—A criticism of "de-growth" and a plea for "a-growth". *Ecological Economics, 70,* 881–890.
Van der Werff, E., Steg, L., & Keizer, K. (2013). It is a moral issue: The relationship between self-identity, obligation-based intrinsic motivation and pro-environmental behaviour. *Global Environmental Change, 23,* 1258–1265.
Zagonari, F. (2015). Technology improvements and value changes for sustainable happiness: A cross-development analytical model. *Sustainability Science, 10,* 687–698.
Zagonari, F. (2016). Four sustainability paradigms for environmental management: A methodological analysis and an empirical study based on 30 Italian industries. *Sustainability (Switzerland), 8,* 504–537.