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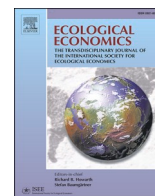
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Multidimensional welfare indices and the IPCC 6th Assessment Report scenarios[☆]

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ABSTRACT

The IPCC's 6th assessment report (AR6) has provided a wide range of variables and scenarios that meet climate targets of varying ambition. Many variables reported in the AR6 affect human welfare through climate change and mitigation, including but not limited to economic output, the natural environment, human health, and food and energy supply. In some of these dimensions, trade-offs exist between better performance in welfare-relevant dimensions and reaching more ambitious climate targets. Here, we apply recent advances in the theoretical multidimensional measurement of welfare, like the Human Development Index, to the AR6 database. The welfare metric is based on a welfare function approach, simple to apply, and intuitive. We apply a range of specifications of the welfare metric, aiming to derive robust rankings of climate policy targets that perform best in terms of the multidimensional welfare index. Across a large range of weights on welfare-relevant variables, we find that lower temperature is associated with higher welfare in 2100 unless there is a high weight on food supply.

1. Introduction

Human development in the 21st century faces significant challenges. The Sustainable Development Goals call for human progress in a wide range of economic, social and ecological dimensions (United Nations, 2019), where there may be synergies in achieving some goals but where progress in other dimensions may compete for limited resources (Moyer and Bohl, 2019). The Sustainable Development Goals are thus broadening our understanding of what is important for human development for the next decades. While economic growth has been an engine of development in the 20th century, though not universally (Ranis et al., 2000; Suri et al., 2011), the Human Development Index (HDI) introduced in 1990 adds education and health to economic development as important determinants of human wellbeing (UNDP, 2020). The HDI allows ranking different development pathways across space and time to identify strategies that further human wellbeing. Considering the

Sustainable Development Goals, multidimensional welfare metrics such as the HDI need to be amended to include more dimensions, most importantly those pertaining to environmental issues such as climate change and biodiversity.

We apply a class of multidimensional welfare metrics based on the HDI to rank alternative scenarios of climate change mitigation. The welfare metric aggregates indicators for economic development, education, health, climate change and biodiversity. By ranking alternative scenarios of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), we test in which cases meeting more stringent climate targets improves welfare. We find that in many scenarios, welfare improves with lower global temperature. There are, however, important exceptions. First, strong climate policy is associated with lower welfare in the short-term especially if there is low substitutability between different dimensions. In the short term, costly climate action hinders economic development and adversely affects food supply that

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cannot be offset by progress in other indicators if substitutability is low. Second, welfare improves if less stringent climate targets are met when there is a relatively high weight on food supply, because stringent climate change mitigation competes with higher global food supply.

Our welfare metrics extend concepts such as the Planetary pressures adjusted HDI (PHDI, (Roy et al., 2023)) by incorporating environmental indicators for human wellbeing but allowing for flexible assumptions about normative parameters, such as the OECD’s Better Life Index (Decancq, 2015). The normative parameters allow varying the importance that certain dimensions play in aggregate welfare and allow varying in how far a low score in one dimension may be offset by a high score in another dimension. The welfare metric thus quantifies trade-offs between reaching multiple dimensions of human development. Such trade-offs have been described in previous literature (Moyer and Bohl, 2019; von Stechow et al., 2016), and make it more difficult to prioritize alternative development strategies. Indeed, assessing environmental dimensions or sustainability in a broad sense using a unique index has many conceptual and practical issues. While our approach is based on a conceptually founded welfare function approach, notably weighting exhibits still a great degree of arbitrariness (Böhringer and Jochem, 2007), which we address by performing a large sensitivity analysis on the vector of weights applied. Our indices also satisfies the conditions of being “meaningful” environmental indices (Ebert and Welsch, 2004). Our welfare metrics allow ranking alternative strategies and explicitly stating normative preferences about the importance of different dimensions, and their trade-offs, for human wellbeing.

We apply our welfare framework to the question of climate change mitigation. Limiting climate change is one of the key societal goals over the next decades as unmitigated climate change leads to significant impacts on human wellbeing (Franchini and Mannucci, 2015; IPCC, 2022; Pecl et al., 2017). However, climate change mitigation also has adverse impacts on other indicators for human wellbeing that belong to the Sustainable Development Goals (IPCC, 2022). We thus aim at investigating when meeting stringent climate change targets improves global welfare, and when and why it does not. In that respect, our paper is part of a growing literature highlighting the importance of a multidimensional perspective in the context of environmental and climate policy (Botzen and van den Bergh, 2014; Pillarisetti and van den Bergh, 2010; van den Bergh, 2010), for instance using Integrated Assessment Models (Bastien-Olvera and Moore, 2020; Drupp and Hänsel, 2021). Here we explore such multidimensional approaches in the rich AR6 scenario database to draw more general conclusions regarding welfare.

The paper is organized as follows. Section 2 summarizes our methods by introducing the welfare metric and the climate change mitigation database. Section 3 shows the indicators for welfare that follow from the database as well as presents our results on welfare. Section 4 shows a large ensemble of weights used, and Section 5 discusses caveats of the paper. Section 6 concludes.

2. Methods

2.1. Multidimensional welfare metrics

Multidimensional indices are useful to assess welfare or sustainable development in a concise and transparent way when multiple dimensions are deemed relevant. In this paper, we consider a broad class of such indices that encompass and generalize some existing approaches.

To be more specific, let ℓ denote the number of dimensions considered in the analysis, and $(I_1, I_2, \dots, I_\ell)$ the vector of the ℓ indicators for the performance in each dimension. The general formula for our synthetic indicators will be¹:

$$I = \left(\sum_{j=1}^{\ell} \omega_j \times (I_j)^{1-\rho} \right)^{1/(1-\rho)} \quad (1)$$

where ρ is the substitutability parameter and ω_j the weight put on dimension j .

The substitutability parameter measures how difficult it is to compensate for a bad score in some dimension with a good score in another dimension. When $\rho = 0$, we are in a situation where dimensions are completely substitutable. When $\rho \rightarrow \infty$, there is no compensation possible between dimensions.

The weights describe the importance of each dimension. To be meaningful, those weights must be applied to commensurable variables. In turn, commensurability depends on how the indicators are normalized. (Böhringer and Jochem, 2007) highlight that there are three key steps in the construction of multidimensional indices: aggregation, weights, and normalization.

The aggregation method displayed in Eq. (1) is characterized by (Ebert and Welsch, 2004) in a case where the different indices are comparable and ratio-scale measurable: this requires a common meaningful 0 for all dimensions, a comparable value at 1, and the independence of measurement to changes in scales. To ensure those conditions, the common practice is to normalize indices so that 0 corresponds to the worst imaginable (or acceptable, or existing) value of the variable, 1 corresponds to the best imaginable (or acceptable, or existing) value of the variable, and the index is interpreted as the relative achievement of the best situation. So, we need that the indices are normalized, i.e. to decide explicitly the cases where they take values 0 and 1. In the HDI methodology, these are called “dimension indices”. We discuss the exact formula for the normalization of the indicators in the next subsection. Remark that if instead we require the weaker condition that variables are non-comparable but still ratio-scale measurable, that is we need not set the value at 1, only case $\rho = 1$ remains possible.

Even within our family of indices displayed in Eq. (1), there is still a large variety of choices depending on the value of parameter ρ and of the weights. As rightly pointed out by (Böhringer and Jochem, 2007), there is some degree of arbitrariness (or “subjectivity” as they put it) in the choice of those values that reflect normative views. To be transparent about this, the present paper explores how those changes affect welfare evaluation.

Our family of indices covers several special cases that have been proposed in the literature. In particular, the HDI is a key multidimensional measure of development produced annually by the United Nation Development Program (see UNDP, 2020). It is based on indicators of three dimensions of human development: a normalized indicator of education I_E (average years of schooling), a normalized indicator of health I_H (life expectancy), and a normalized indicator of income I_Y (log of average income).

These indicators are combined in a specific way. The initial formula was an arithmetic mean:

$$HDI_{old} = \frac{1}{3}(I_E + I_H + I_Y) \quad (2)$$

But in 2010, a new formula was introduced, namely a geometric mean:

$$HDI_{new} = (I_E \times I_H \times I_Y)^{1/3} \quad (3)$$

As explained by (Fleurbaey, 2018), the new formula implies some complementarity between the dimensions. This reflects a preference for balanced development in which income, health and education make progress together. The new formula implies a specific assumption about the degree of substitutability: the old formula assumed perfect substitutability, while the new formula allows more limited substitution possibilities. Both formulas assume equal weights on all three variables. The simple sum version of the HDI has for instance been applied to the

¹ In the case $\rho = 1$ the formula becomes $I = \prod_{j=1}^{\ell} (I_j)^{\omega_j}$.

status and benefits from the oceans (Halpern et al., 2012), but it has been shown that the more general framework proposed in the present paper can significantly alter the assessment of the human-ocean system (Rickels et al., 2014).

The HDI has been extended in several ways. First, an Inequality-adjusted Human Development Index (IHDI) was proposed to adjust for inequality in each dimension. To do so, it draws on Atkinson (1970) approach of adjusting social welfare for inequality, and on the associated family of inequality measures. Specifically, let X a dimension of interest and (X_1, \dots, X_n) denote the underlying distribution in that dimension. The Atkinson index A_X^ϵ for parameter $\epsilon \geq 0$ is²

$$A_X^\epsilon = 1 - \left(\frac{1}{N} \sum_{i=1}^n \frac{X_i^{1-\epsilon}}{\bar{X}} \right)^{\frac{1}{1-\epsilon}} \quad (4)$$

where $\bar{X} = \frac{1}{N} \sum_{i=1}^n X_i$ is the average value.

The IHDI adjusts each variable (life expectancy, mean years of schooling and disposable household income) for inequality, using the Atkinson index with parameter value $\epsilon = 1$. The formula is then:

$$IHDI = ((1 - A_E^1)I_E \times (1 - A_H^1)I_H \times (1 - A_Y^1)I_Y)^{\frac{1}{3}} \quad (5)$$

Parameter ϵ in the Atkinson index embodies the degree of aversion to inequality. When $\epsilon = 0$ (no inequality aversion) the Atkinson index is always equal to 0. When $\epsilon \rightarrow \infty$, we tend to a Rawlsian case that focuses on the worst-off and the Atkinson index is equal to one minus the ratio between the minimal value and the average value.

More recently (UNDP, 2020), the UNDP has introduced another index named Planetary pressures-adjusted HDI (PHDI). It adjusts the HDI for the level of planetary pressures through a composite index P (based on CO2 emissions per capita and material footprint per capita) that takes value 0 for maximal pressure, and value 1 for minimal pressure. The formula is:

$$PHDI = P \times (I_E \times I_H \times I_Y)^{1/3} \quad (6)$$

The PHDI corresponds to a special case of our general Eq. (1) where $\rho = 1$ and the weight on the Planetary pressure index P has as much importance as the three other indices combined.

There are important limitations of indices in the HDI family (HDI, IHDI and PHDI), especially from the viewpoint of analyzing climate policy. First, they all make very specific assumption both on parameter ρ and on the weights. Regarding the weights, this is for instance in contrast with the Better Life Index of OECD that allows flexibility in that respect (Decancq, 2015). There is a lack of justification for the specific assumptions of HDI (Decancq et al., 2009). Second, all the indices except the PHDI neglect important dimensions that particularly matter, as the focus focuses on three anthropocentric dimensions (income, education, health). The PHDI includes the adjustment for planetary pressures. However, it does so in a specific way (specific weight on HDI and planetary pressures, specific substitutability). Also, by focusing on the per capita footprint of humans, it neglects other aspects like the state of biodiversity.

Inequality adjustment in the IHDI offers an interesting enrichment of the welfare framework, although the methodology again takes a specific value for inequality aversion in the Atkinson family (namely $\epsilon = 1$). However, in this paper we have not been able to include this important dimension of human sustainable development. Indeed, the AR6 database only has data at the regional level, which is a not very detailed level for inequality analysis. We keep this for future research.

² In the case $\epsilon = 1$ the formula becomes

$$A_X^1 = 1 - \frac{(\prod_{i=1}^n X_i)^{1/n}}{\bar{X}}$$

In this work, our central case will be $\rho = 1$ and equal weight on different dimensions that we describe below. This central case corresponds to a situation where the different dimensions need not to be measured on the same scales, and it is a typical dividing case between small a large substitutability. It is also a common choice in the literature (this is the choice made in the new version of the HDI and it is also often in IAMs including multidimensional welfare measurement (Drupp and Hänsel, 2021)). But we will also consider how the choice of those parameters may change our results.

2.2. Data selection from the AR6 scenario database

We compute the welfare level of scenarios in the AR6 scenario database (Byers et al., 2022). The AR6 scenario database is part of the Sixth Assessment Report of the IPCC. The database collected model-based scenarios where varying climate change targets are met, and reports the level of key variables related to, e.g., temperature, emissions, and socio-economic dimensions like GDP. In an open call, scenarios could be submitted which belong to a peer-reviewed publication or approved grey literature. The AR6 database includes over 3000 scenarios from close to 200 modelling frameworks.

In accessing the AR6 database using the “pyam” package (Huppmann et al., 2021), we evaluated a total of 1656 variables, which are available for at least one scenario and model. However, a large part of the variables comprises energy system variables and (post-processed) climatic variables at the global level. Moreover, most variables are scarcely reported, and only available for a small subset of models. Finally, many variables measure very similar dimensions (e.g., capacity, investment, costs, or installation data on energy technologies). Therefore, we limited the number of scenarios and models, aiming to have a sufficient number of models and scenarios while capturing the largest possible number of dimensions, notably economic affluence, health, nutrition, energy availability, and land-use. Since emission data is widely available, and pollutants have different impact channels, we included two types of pollutants, and finally we also added global temperature as just one dimension capturing global warming. Ultimately, our multidimensional welfare measure includes seven indicators that are part of the AR6 scenario database. These indicators represent relevant well-being dimensions:

- Temperature represents the degree of global warming (GMT increase) and related impacts
- NOx emissions are a proxy for health impacts
- Sulfur emissions are a similar proxy for health impacts
- Food supply is a proxy for health impacts related to changes in agriculture and food consumption
- Electricity production is taken as an indicator of energy access and clean energy provision. Moreover, it has been found to be highly correlated with education levels (see Ahmad et al., 2014; Banerjee et al., 2021; Kanagawa and Nakata, 2008). In general, it has indeed been shown that access to affordable, clean, and safe sources of energy is essential to achieving universal and equitable access to education (United Nations Department of Economic and Social Affairs, 2014), which we cover through this indicator.)
- GDP is the usual index of economic development
- Forest cover is an index of biodiversity preservation

For the welfare metric, NOx and sulfur emissions, food supply, electricity and GDP enter on a per-capita basis. In addition, we combine the indicators for NOx and sulfur emissions to one indicator by letting them equally share a welfare weight.

To calculate welfare, the seven variables are transformed into dimension indicators, meaning that they are normalized between a worst state (corresponding to a value of 0) and a best state (corresponding to a value of 1). Minimum and maximum values are set to perform this transformation of indicators.

More specifically, the dimension indicators are computed in the following way, depending on whether we measure a good or a bad: for the goods log of GDP, Food supply, Electricity, and Forest Cover, the indicator is $\bar{I}_j = \frac{I_j - I_{j,min}}{I_{j,max} - I_{j,min}}$; for the bads Temperature, NOx emissions, and Sulfur emissions, the indicator is computed as $\bar{I}_j = \frac{I_{j,max} - I_j}{I_{j,max} - I_{j,min}}$.

Thus, we need minima and maxima ($I_{j,min}$ and $I_{j,max}$) to enter the indicator specification for the seven dimensions. As elaborated in 2.1, for a good (bad) the minima should correspond to some worst (best) case while the maxima reflect a best (worst) case. To define the extrema for our analysis, we take a pragmatic approach and either set these extrema equal to the minima and maxima across all scenarios and time steps in the AR6 database (after removing outliers) or use exogenous reference scenario. Doing so, we know that the level of indicators varies between sensible boundaries that match the AR6 database.

For all variables except GDP, maxima correspond to values observed in the AR6 database (see Table 1). We take this approach because values in AR6 may go beyond observed data as the economy transforms to be either more or less climate friendly. Food supply is a good example, where future production may exceed observed historical values. For GDP, we keep the maximum of 75,000 USD set by the United Nations' definition of the HDI. This means that GDP may go beyond this maximum in some scenarios, which is however already the case for some countries today.

For minimum values, we either use AR6 minima or sensible exogenous data. For temperature, a value of zero refers to pre-industrial levels. For NOx and sulfur emissions, sources are both natural and anthropogenic where both sources can change with scenario projections. We use the AR6 database for their minima. For electricity, we set the value at zero as life without education is possible (the minimum expected schooling years are zero in the HDI definition of the United Nations). For our food indicator, we use the "Minimum dietary energy requirement" of the FAO. For GDP we use the minimum value used in the HDI by the United Nations. Concerning forest land cover, a minimum is hard to define, and we rely on the observation that some regions do not have any forest and set the minimum to zero.

In Fig. 1, the seven variables that enter our welfare metric are depicted as the AR6 data base reports them, together with population as we use per-capita values for several indicators (emissions, electricity, food supply, GDP). One can see that the scenarios cover a range of possible futures. Population and socio-economic activity including climate policy drive temperature change, emissions of air pollutants, land use change as well as energy and food supply. As we intend to compare the welfare level of different scenarios, we limit our analysis to only scenarios of the second Shared-Socioeconomic-Pathway (SSP2).

Fig. 1 shows that the number of scenarios that report certain variables varies: Food Supply is reported by only few scenarios compared to, for example, Temperature or GDP. Overall, we find a total of 198 scenarios that belong to SSP2 and offer values of all 7 variables chosen to enter our welfare metric.³ Table 2 reports which models provided the 198 scenarios, which are in most cases the same across categories. In addition, we show how many scenarios belong to the 7 climate assessment categories used by the IPCC. These categories vary from meeting the stringent climate change target of below 1.5 °C (C1) to high temperature changes of 4 °C (C7). (See Table 3.)

Already by observing these variables for different climate target categories, several important trends are visible: the more stringent scenarios in line with the 1.5-degree target (C1-C2, blue colors) show clearly higher electricity production (due to electrification being an important mitigation strategy in the transportation and buildings sector), and a higher forest land cover. On the other hand, air pollutant emissions are significantly lower. GDP and Food supply show a mixed picture, where costs of

mitigation and impacts on land-use due to bioenergy crops can lead to higher or lower values under the stringent scenarios.

3. Results

We first analyze the indicators derived from the seven variables that enter our welfare metric. We structure our analysis along the seven climate impact categories of the IPCC that rank the stringency of the entire temperature trajectory until 2100 (see Table 2). This allows us to assess how climate targets influence each of the indicators. We next analyze how different weighting schemes and levels of substitutability to aggregate indicators shape the correlation between yearly temperature levels and welfare.

Fig. 2 reports the indicators for the years 2030, 2060 and 2100 and only for the 198 scenarios that reported all 7 variables. The indicators take on values between 0 and 1.2. To foster comparison between all 7 variables, the scale in Fig. 2 is 0 to 1.2 even if a certain variable's indicator varies little (see Fig. 8 in the Appendix for adjusted scales). For each year, indicators are grouped by the climate assessment categories of the IPCC (C1 to C7). Fig. 9 in the Appendix shows the correlation matrix between all indicators for the years 2060 and 2100.⁴

Temperature is one of the key variables reported in the AR6 database. Fig. 2 shows that the indicator for Temperature is at roughly 0.7 across all scenarios in 2030 and declines over time unless stringent climate targets are met by 2100 (C1 and C2). As expected, a climate category with higher temperature, i.e., going from C1 to C7, exhibits a lower indicator level, where the indicator reaches its lowest value at around 0.3 in 2100 for the category C7.

The indicator for GDP is always above 0.7 and varies around 1 in 2100 (Fig. 2). Note here that we only consider global GDP per capita in the indicator and thus abstract from any national or even subnational income inequality. Driven by economic growth, later points in time exhibit a higher indicator for GDP. There is a slight tendency for GDP to increase with meeting less stringent climate change targets, i.e., going from C1 to C7, but the effect is small as climate change mitigation is expected to cost only a few percentage points of GDP in most scenarios in the AR6 database. Important to note is that the scenarios in the AR6 database do not account for climate impacts.

Meeting more stringent climate change targets tends to improve the indicators for NOx emissions, Sulfur emissions and Forest cover in each time step (Fig. 2). The indicators tend to increase with lower temperature because climate change is mitigated through less fossil fuel combustion, which releases these emissions, and afforestation. Both NOx and Sulfur emissions' indicators tend to increase over time and almost reach 1 in 2100. If moderate to stringent climate targets are met, the indicator for Forest cover also increases over time.

Higher forest cover competes with food supply for land. Fig. 2 shows that, in each time step, the indicator for Food supply tends to increase when less stringent climate change targets are met. To reiterate, in the scenarios in the AR6 database there are by construction no impacts from climate change on the economy, neither on energy nor on agriculture. While this is clearly a limitation, further integration of climate mitigation and impacts is a very active research field, for which however no large-scale databases of scenarios are yet available. The indicator is below 0.5 in most scenarios and tends to increase over time, though only to a limited degree.

The indicator for electricity is rather low across all scenarios and tends to increase over time. Meeting more stringent climate change targets is associated with an increase in the indicator, albeit to a limited extent (Fig. 2), as the decarbonization is typically leading also to a further electrification of energy end uses in the transportation and buildings sector (Rockström et al., 2017).

³ We removed one scenario that belongs to the C8 climate category for comparability.

⁴ We do not show the correlation matrix for 2030 as temperature only varies very little.

Table 1
Minima and Maxima that are used in the welfare indicators.

Variable [unit]	Temperature [K]	NOx Emissions [kg/cap]	Sulfur Emissions [kg/cap]	Electricity [GJ/cap/yr]	Food Supply [kcal/cap/day]	GDP [USD/cap/yr]	Forest Cover [share of total land]
Type of variable	Bad	Bad	Bad	Good	Good	Good (log enters indicator)	Good
AR6 variable name	“AR6 climate diagnostics Surface Temperature (GSAT) MAGICCv7.5.3 50.0th Percentile”	“Emissions NOx”	“Emissions Sulfur”	“Final Energy Electricity”	“Food Energy Supply”	“GDP PPP”	“Land Cover Forest” combined with “Land Cover”
minimum	0	0.49	0.12	0	1827	100	0
Source	MAGICC (relative Temperature)	AR6	AR6	see text	FAO ^a	UN ^b	see text
maximum	5.25	59	58	254	4505	75,000	0.61
Source	AR6	AR6	AR6	AR6	AR6	UN5	AR6

^a FAO Food and Agriculture Organization (2020). *Food Security Indicators*. Access - Prevalence of undernourishment, yearly estimates. Update 13 July 2020.

^b https://hdr.undp.org/sites/default/files/2021-22_HDR/hdr2021-22_technical_notes.pdf.

AR6-database: variables for welfare metric

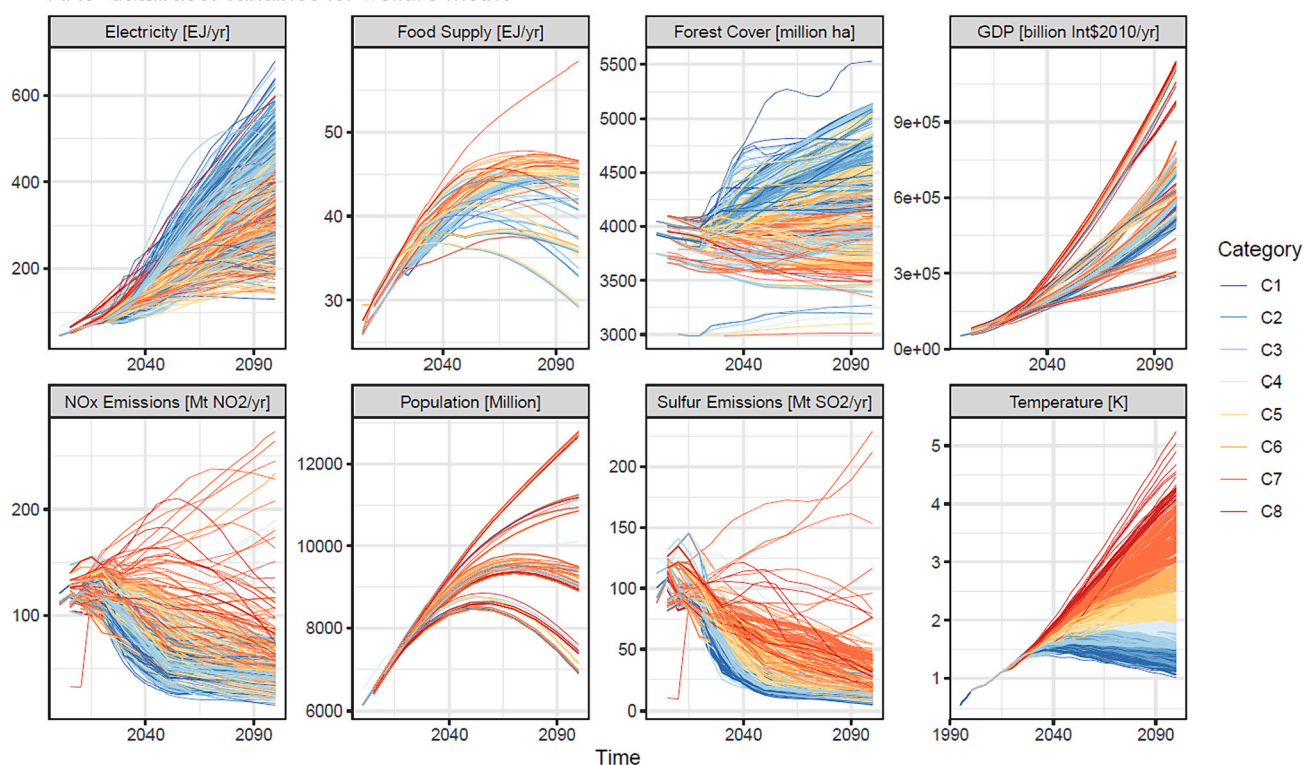


Fig. 1. Variables used for the welfare metric across all AR6 scenarios over time. Colors indicate the climate assessment category of the AR6 data base (see Table 2).

In conclusion, 5 out of 7 seven indicators tend to increase when more stringent climate change targets are met (Temperature, NOx and Sulfur emissions, Forest Cover, Electricity) while the other two indicators do not (GDP, Food supply). Fig. 9 in the Appendix confirms these relationships through correlation between the temperature indicator and all other indicators in 2060 and 2100. In addition, all indicators except for Temperature tend to increase over time.

The behavior of the seven indicators translates to welfare depicted in the last panel of Fig. 2, where the indicators are aggregated with a substitutability of $\rho = 1$ and equal weights (see Footnote 8). Welfare tends to increase over time and when more stringent climate change targets are met. In 2030, welfare is almost constant across climate assessment categories: meeting the different climate targets has only minor impacts on bio-socioeconomic variables in the short term and any variation is balanced by the welfare aggregation. In 2060, welfare is on average higher in almost all scenarios compared to 2030, which reflects

the positive time trend of most indicators. The positive effect of meeting more stringent climate targets on welfare is already felt in 2060: on average, welfare is highest for stringent mitigation categories C1 and C2, which is higher than in C3 and so on. As 5 out of 7 indicators tend to improve with meeting more stringent climate change targets, welfare improves as well. These observations carry over to 2100: welfare tends to be higher compared to 2060 and welfare increases with more ambitious climate change targets. However, welfare in some scenarios of C7 is below some welfare levels in 2030. As some indicators are at their lowest level in 2100 (Temperature, Forest cover), overall welfare could decline if climate change is not mitigated.

Fig. 3 explores welfare in the AR6 scenario database when normative parameters take on different values. We tested the combination of three values for substitutability and three sets of welfare weights. For the former, we assume perfect substitutability ($\rho = 0$), limited substitutability ($\rho = 1$) and low substitutability ($\rho = 5$). For the latter, we vary

Table 2

Number of scenarios, and numerical model submitting them, that included all seven variables chosen for the welfare metric in the AR6 database and belong to SSP2; reported by IPCC climate category.

Category	Description	Number	Models
C1	Limit warming to 1.5 °C (>50%) with no or limited overshoot	13	AIM/CGE 2.2, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C2	Return warming to 1.5 °C (>50%) after a high overshoot	21	AIM/CGE 2.2, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C3	Limit warming to 2 °C (>67%)	56	AIM/CGE 2.1, AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0
C4	Limit warming to 2 °C (>50%)	31	AIM/CGE 2.2, IMAGE 3.0, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C5	Limit warming to 2.5 °C (>50%)	39	AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C6	Limit warming to 3 °C (>50%)	18	AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0
C7	Limit warming to 4 °C (>50%)	20	AIM/CGE 2.1, AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0

Table 3

Regression results of the welfare index on GMT temperature increase.

Weight	Rho	Point estimate	Standard error	t-Statistic
Low GDP	0	−0.05100	0.00269	−18.95046
Equal	0	−0.04261	0.00244	−17.46432
High GDP	0	−0.00259	0.00205	−1.26447
Low GDP	1	−0.05067	0.00388	−13.05808
Equal	1	−0.04786	0.00373	−12.83819
High GDP	1	−0.00509	0.00210	−2.42060
Low GDP	5	−0.02590	0.00561	−4.61928
Equal	5	−0.02705	0.00586	−4.61814
High GDP	5	−0.04729	0.01050	−4.50255

the relative weight of GDP: the indicator for GDP receives a low, equal, or high weight relative to all other indicators⁵.

Broadly summarizing Fig. 3, welfare tends to increase when more stringent climate change targets are met, and welfare tends to increase over time. Welfare increases because most indicators tend to increase over time and with more stringent climate change targets (Fig. 2). There are important exceptions to this broad picture.

First, average welfare in 2030 is lower in the stringent climate target category C1 compared to the lenient C7 category if substitutability is low ($\rho = 5$, bottom row), though the magnitude of the effect appears small. There can thus exist a trade-off between meeting stringent climate policy targets and some welfare dimensions in the short term.

Second, the relative importance of GDP in the welfare metric matters. In 2030 and 2060, average welfare tends to be slightly lower with meeting stringent climate change targets C1 and C2 compared to C3–C5 if the weight on GDP is high (column to the right in Fig. 3) and substitutability between indicators is perfect or limited ($\rho = 0$ or 1, top and middle row in Fig. 3). Meeting more stringent climate change targets induces costs for the current and near-term generations, which leads to lower welfare if the weight on those costs in welfare is high.

Third, it is important whether high scores of some indicators can substitute low scores of other indicators. If substitutability between indicators is low ($\rho = 5$, bottom row in Fig. 3), welfare does not further decrease across climate categories C3 to C7 in 2060 and 2100 but shows a more U-shaped form. On average, welfare is highest in the C1 and C2 categories and then declines to almost constant levels in C3 to C7. Interestingly, some scenarios in the C7 category have higher welfare than in the C6 and even the C5 category. With lower substitutability, welfare is driven more by those indicators that take on low levels. Fig. 2 shows that the indicators for Electricity and Food supply are on average lowest compared to the other indicators, as well as Temperature in 2100 when less stringent climate targets are met. While the Temperature indicator increases with more stringent climate change targets, Food supply tends to be negatively correlated with more stringent climate

⁵ Weights are (0.01,0.5,0.5,1,1,1,1) for low GDP, (1,0.5,0.5,1,1,1,1) for equal weights and (100,0.5,0.5,1,1,1,1) for high GDP, where the order of variables is GDP, NOx Emissions, Sulfur Emissions, Temperature, Electricity, Food Supply, Forest Cover. Weights are normalized to sum to 1 for the welfare computation.

change targets and the indicator for electricity takes on higher values in some scenarios in the C7 category than in the C5 and C6 scenarios. Thus, for low substitutability, welfare displays the trade-off between increasing welfare through lower temperature versus higher food, and somewhat electricity supply. Some scenarios with high temperature but higher food and electricity supply exhibit higher welfare compared to scenarios with low temperature and lower food and electricity supply if substitutability is low.

Lastly, average welfare does not increase with time if less stringent climate targets are met (C7), GDP receives a low weight and there is perfect substitutability between indicators (top left panel in Fig. 3). In this case, economic growth cannot offset higher temperatures and the sharp decrease in the indicator for temperature over time drives the declining welfare level.

Taken together, for our central specification, Figure Fig. 4 shows the multivariate welfare index across the seven scenario categories of the IPCC in 2100. It shows the secular decline in average welfare as the temperature target becomes less stringent, while also for low temperature targets, the model uncertainty is larger indicating that the Paris Agreement compatible scenarios exhibit significant model differences and uncertainty. Only for the most stringent 1.5-degree target without or with overshoot (C1 and C2) the ranking is reversed, in that the scenarios without overshoot show a slightly lower level of welfare on average, albeit also a higher degree of uncertainty.

When looking at the relationship between the multidimensional welfare index, the parameter of the substitutability (ρ), and GDP per capita, Fig. 5 shows that in general (here shown for 2100), higher values of ρ lead to a lower value of welfare, and a larger dispersion. Moreover, higher values of GDP predominantly increase welfare.

When comparing the value of welfare to temperature increase by the end of the century, across models and scenarios, Fig. 6 highlights that lower values of global warming are associated with higher values of welfare, and the effect tends to be stronger for lower values of rho.

When comparing the slope as of how the welfare index on average changes with global mean temperature, Table 3 shows a change of between −0.01 and −0.05 of welfare for each degree of additional warming across scenarios, with a preferred value of −0.048 for equal weights and a unity elasticity.

4. Large ensemble of individual variable weights

We test our findings with a large set of runs varying the weights of all variables individually to capture a full simplex of weights. A variable either receives a weight of 100, 1 or 0.01 and we compute all combinations of those weights. After normalizing weights to sum to 1, 665 unique sets of weights emerge.⁶ Combined with the three values for ρ , we have $3 \times 665 = 1995$ combinations of normative parameters. We then run the regressions from the previous section across all scenarios to

⁶ Note that as explained in Section 2, the indicator for NOx and Sulfur emissions are combined into one indicator that shares the same weight as the other dimensions, thus taking on values of 50, 0.5 and 0.005.

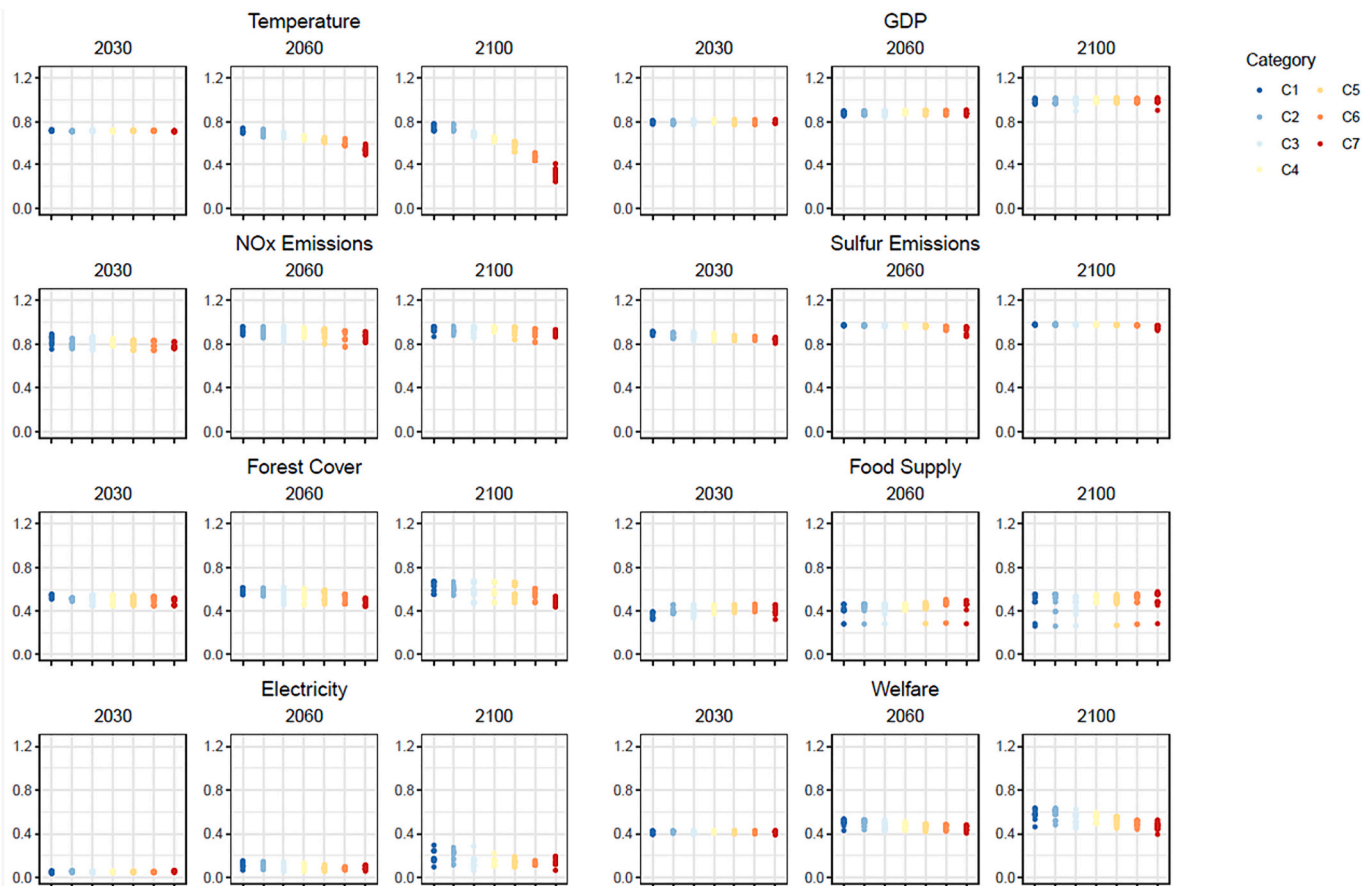


Fig. 2. Indicators of the seven variables entering the welfare metric for three points in time, and the welfare level for an elasticity of substitutability of $\rho = 1$ and equal weights (see Footnote 8). Colors indicate the climate assessment category of the AR6 database.

estimate the relationship between the degree of global warming (GMT increase) and the welfare index.

We first investigate the relationship between welfare and temperature in 2100. The estimated slope for all scenarios is shown in Fig. 7, where we indicate by the color the relative weight of Food Supply, which we find to be the most influential variable in potentially affecting this relationship.⁷ Only for relatively high weights for Food Supply, approaching one (in blue) at the extreme, the relationship becomes slightly positive, indicating that the scenarios without stringent climate action and hence much higher degree of potential warming could lead to a higher level of welfare. In all other cases, the relationship is negative as found in the previous section. Considering all other variables, as shown in Fig. 10 in the Appendix, we don't find other variables for which a high weight leads to welfare and temperature increase being positively correlated. In terms of the absolute value of this relationship the median and mode lie within the range of -0.01 and -0.05 , as reported in the preceding section, but can extend to up to -0.20 , and in the extreme cases of highest weights on Food Supply turn to $+0.01$.

The average of the welfare index across all models and over time is 0.46, while its standard deviation in the whole sample with all weights and elasticity specification is 0.26. Therefore, we can conclude that the estimated impact of one degree warming on welfare is also sizable. For our preferred estimate of a decrease in welfare of 0.048 with 1 degree of warming (equal weights, medium substitutability), the estimated impact is around one-fifth of the standard deviation in the sample. Still, it can reach up to one standard deviation of the welfare index, which is a very

wide range on a scale from 0 to 1. In equivalent terms, a reduction in per capita GDP of 39% on average would lead to the same decrease in welfare as 1 degree of warming for our preferred estimate.⁸

Fig. 11 and Fig. 12 in the Appendix show the relationship for 2060 and 2030, respectively. Here, differences in temperature increase are less pronounced across scenarios. For 2060 and for most weights and parameters considered, we find a similar relationship between welfare and temperature increase as for 2100, while now a positive relationship is possible of up to $+0.1$ per degree, but only in about 5–15% of the considered welfare weights and substitution elasticity. Only for the very near term (2030), and high elasticity values ($\rho = 5$), welfare always tends to increase with temperature increase (Fig. 12). This finding again highlights the trade-off between reaching more stringent climate mitigation and achieving other development goals, such as economic growth and food supply, in the near term. The trade-off is most pronounced when society views more progress in climate change mitigation as insufficient to offset less progress in other dimensions.

5. Limitations and caveats

This study has some limitations that should be considered. First, the welfare indices make specific assumptions about parameters and weights, albeit they can be changed to reflect substitutability and preferences. Eventually, the final weights used in our indices are still a choice of the analyst (Böhringer and Jochem, 2007). Allowing varying

⁷ In the appendix, Figure 10 shows these estimated slope coefficients colored by the relative weight of each of our variables for 2100.

⁸ We take the slope of the line in Figure 5 for our central case to calculate the absolute change in per capita GDP necessary for a reduction in welfare of 0.048. The absolute change is reported relative to mean global per capita GDP in 2100.

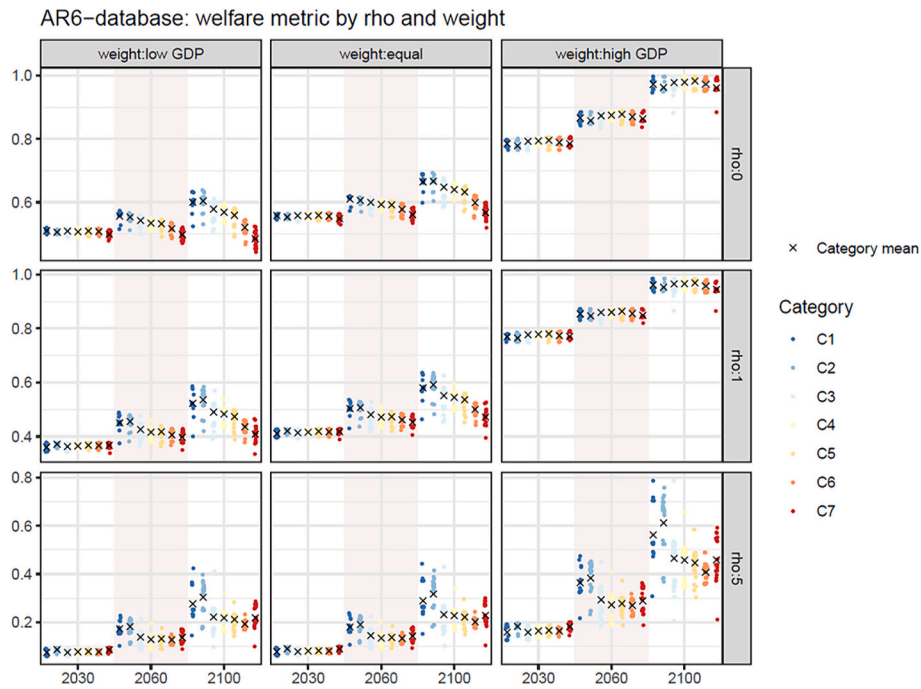


Fig. 3. Welfare metric in 2030, 2060 and 2100 for three values for the elasticity of substitutability ρ , which measures how difficult it is to compensate for a bad score in some dimension with a good score in another dimension ($\rho=0$ (=perfect substitutability), 1, 5). Moreover, we show the values for three sets of weights (low, equal, and high weight on GDP combined with equal weights for the other variables). Colors indicate the climate category.

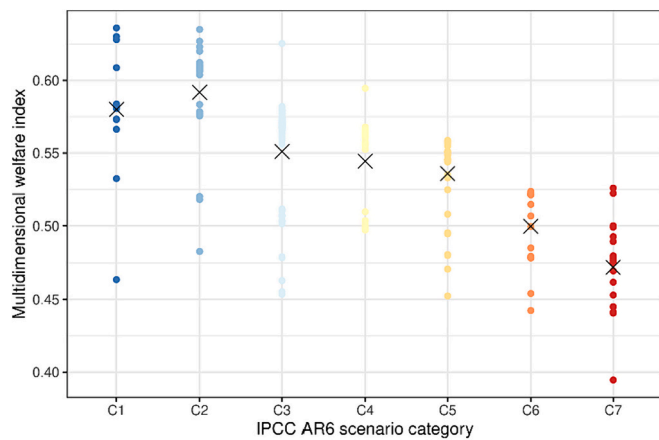


Fig. 4. Central case, welfare across climate categories (equal weights, $\rho = 1$) in 2100; black crosses indicate mean across models.

weights such as in the Better Life Index of the OECD could allow flexibility in that respect (Decancq, 2015). Secondly, the list of available relevant variables (albeit we consider seven dimensions here) for these indices neglect important dimensions such as biodiversity, inequality, or water, which is limited by the database under consideration here. In addition, electricity is only a proxy for education with a partial but not a universal link, which limits the interpretability of our results in terms of this welfare dimension.

Thirdly, the degree of substitutability is not calibrated but rather considering intermediate values of one, while exploring different values in the sensitivity analysis. As for the weights, the choice of substitutability is left to the analyst. Fourth, our analysis is performed only at the global level, masking important regional and country-level differences.

While this analysis can be easily performed also at a finer regional scale, accounting for inequality multiplies the dimensions of results to analyze and visualize through the choice of inequality measure. However, such an analysis could be easily performed, e.g., for a national analysis.

Despite these limitations, our study provides broad valuable insights into the importance of considering multiple dimensions of human wellbeing including environmental considerations, in particular by using a conceptually founded welfare function approach and performing a large sensitivity analysis on the vector of weights and substitution elasticities applied.

6. Conclusion

We analyze indicators derived from seven variables (Temperature, GDP, NOx emissions, Sulfur emissions, Forest cover, Food supply, and Electricity) to measure a multidimensional welfare metric for 198 scenarios of the IPCC AR6 database. The results show that meeting more stringent climate change targets tend to have a positive effect on 5 out of 7 indicators (Temperature, NOx and Sulfur emissions, Forest Cover, and Electricity) while only 2 indicators (GDP, Food supply) tend to increase with less stringent targets. The welfare metric increases over time and with more stringent targets for our central welfare metric. The study also tests different combinations of substitutability and welfare weights and finds that welfare generally increases with more stringent climate targets in 2100. However, meeting these more stringent targets may result in decreased welfare especially in the near-term or with a high weight on food supply. The reason food supply has this particular role is that in the IPCC scenario framework, climate impacts including on agriculture are not considered. On the other hand, the demand for bioenergy in particular drives up crop prices and induces land competition between food and energy crops, leading potentially to decreases of food production.

Overall, we find that even without considering impacts and damages from global warming, human welfare will be affected differently in

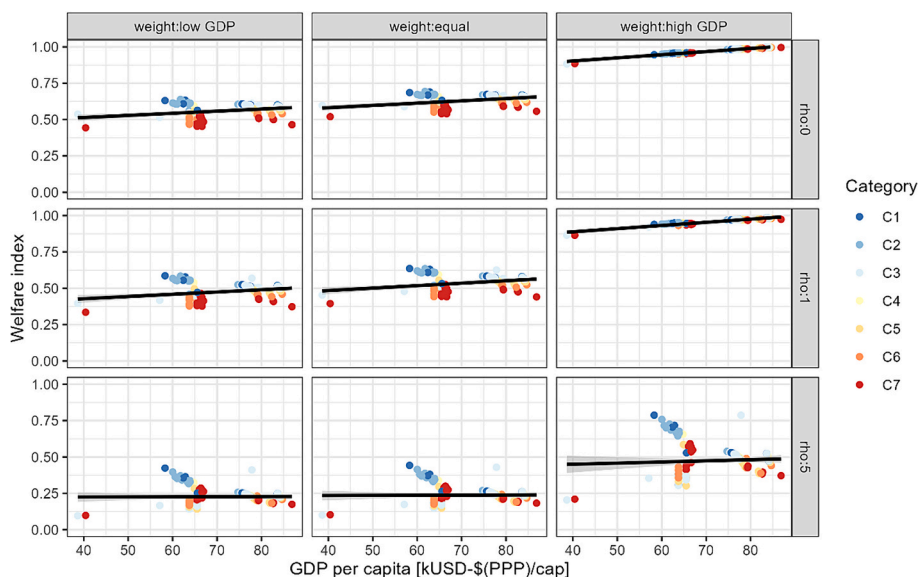


Fig. 5. Relationship of the welfare index with GDP per capita in 2100.

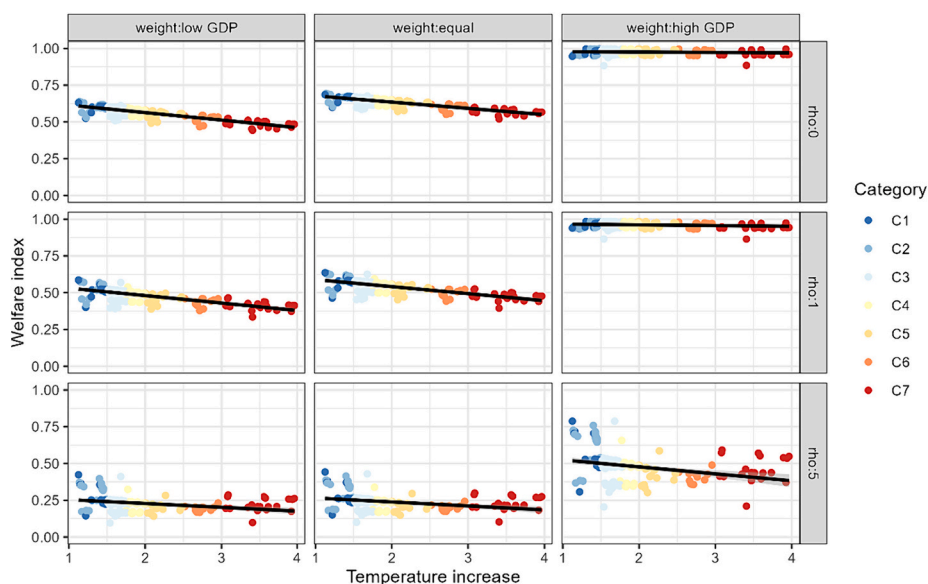


Fig. 6. Welfare index and GMT temperature increase in 2100.

different climate scenarios. The IPCC’s 6th assessment report (AR6) has provided a wide range of variables and scenarios of different levels of climate policy ambition for this analysis. Since in several of these dimension trade-offs exist between more or less stringent climate targets and other dimensions that are relevant for human welfare, we use a general welfare evaluation framework with different weights and substitution elasticities to account for trade-offs and co-benefits. We find that a recently advanced theoretical multidimensional measurement of welfare can then provide a useful tool to derive robust rankings of climate policy stringency. Notably, we find that, on average, a one-degree higher global mean temperature is associated with a loss of about 0.05 on the welfare index at the global level in 2100. When exploring very extreme weights on the different variables, we find that placing a high weight on food supply alters this relationship, at the extreme, leading to slightly higher welfare levels with higher temperatures. For the full set of weights, welfare can decrease up to -0.20 points per degree of global warming.

Our results have important policy implications. Meeting more stringent climate policy targets generally improves human welfare in the medium- and long-term, even when climate change mitigation hinders development in other dimensions of human welfare, such as food availability and income. Thus, efforts to reduce emissions are of utmost importance. However, food security issues could reverse this conclusion as meeting stringent climate targets is often associated with afforestation and generating bioenergy that competes with land use to secure food supply. This important finding indicates that alleviating the trade-off between climate change mitigation and food supply is also of utmost importance. Ambitious efforts to increase food security thus also have important implications for climate policy and overall human welfare.

Finally, one important message from our findings is that GDP losses from stringent climate targets is a very narrow concept of policy costs. Only by adding the six other indicators available in the IPCC database the relationship between target stringency and GDP reverses in most cases. This indicates we should consider welfare beyond GDP

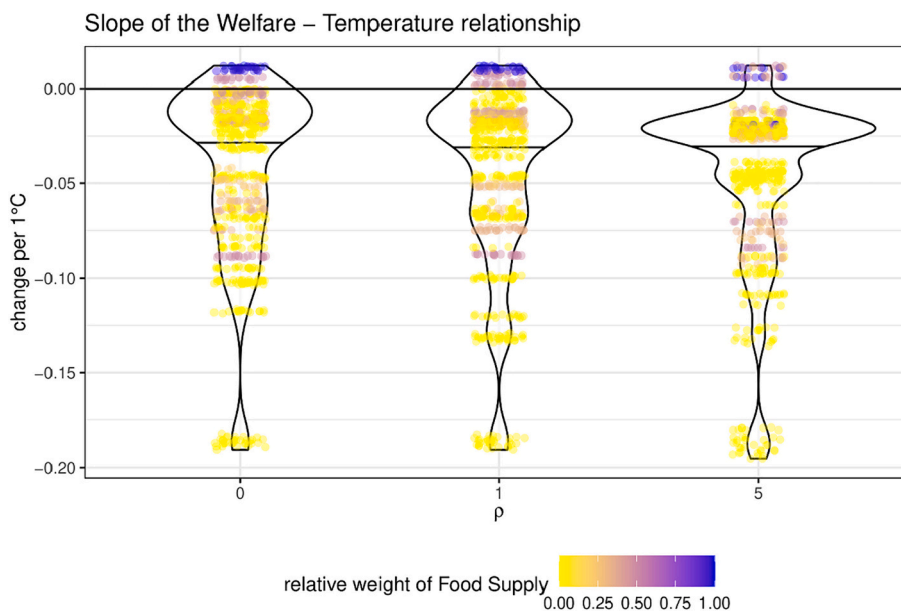


Fig. 7. Estimated slope of the relationship between global mean temperature (GMT increase) and the welfare index, here colored by the relative weight of Food Supply.

(Fleurbaey, 2009), as argued for also in the literature on alternatives to the growth paradigm such as a-growth (van den Bergh, 2011) or post-growth (Hickel et al., 2021) or degrowth (Hickel et al., 2022). Including more important dimensions, for instance, climate impacts (potentially non-linear and with tipping elements), distributional concerns, inequality, leisure and biodiversity impacts etc., may strengthen the beneficial welfare outcomes of the more stringent climate scenarios.

Our results also talk to the literature on the threshold hypothesis (Max-Neef, 1995). The hypothesis is that “for every society there seems to be a period in which economic growth (as conventionally measured) brings about an improvement in the quality of life, but only up to a point – the threshold point – beyond which, if there is more economic growth, quality of life may begin to deteriorate”.

Our results highlight that policies that maximize the growth of conventional economic activity are indeed unlikely to maximize welfare as measured by our more comprehensive measure and that other aspects – like environmental quality – may be more important. On the other hand, economic growth is not incompatible with an increase in welfare or quality of life because we do have economic growth in almost all the scenarios of the AR6 database, even with very stringent climate policy. This is consistent with the results from Van der Slycken and Bleys (2024), who found no conclusive evidence so far regarding the threshold hypothesis in the EU-15.

CRedit authorship contribution statement

Johannes Emmerling: Writing – review & editing, Writing –

original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ulrike Kornek:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Stéphane Zuber:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and code to generate all results and plots is available at https://github.com/JohannesEmm/multidimensional_welfare_ar6.

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Appendix A. Appendix

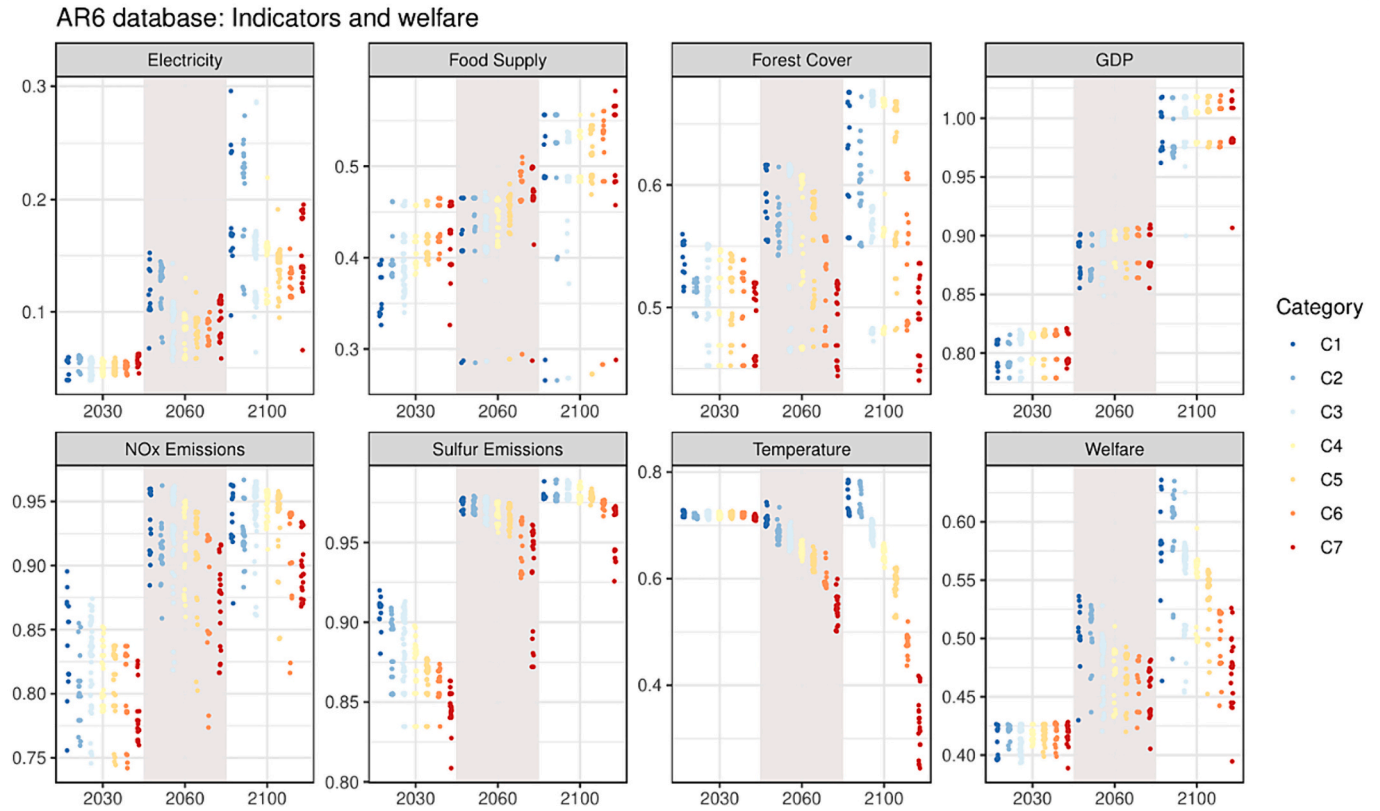


Fig. 8. Indicators of the seven variables entering the welfare metric for three points in time, and the welfare level for $\rho=1$ and equal weights. Colors indicate the climate assessment category of the AR6 database.

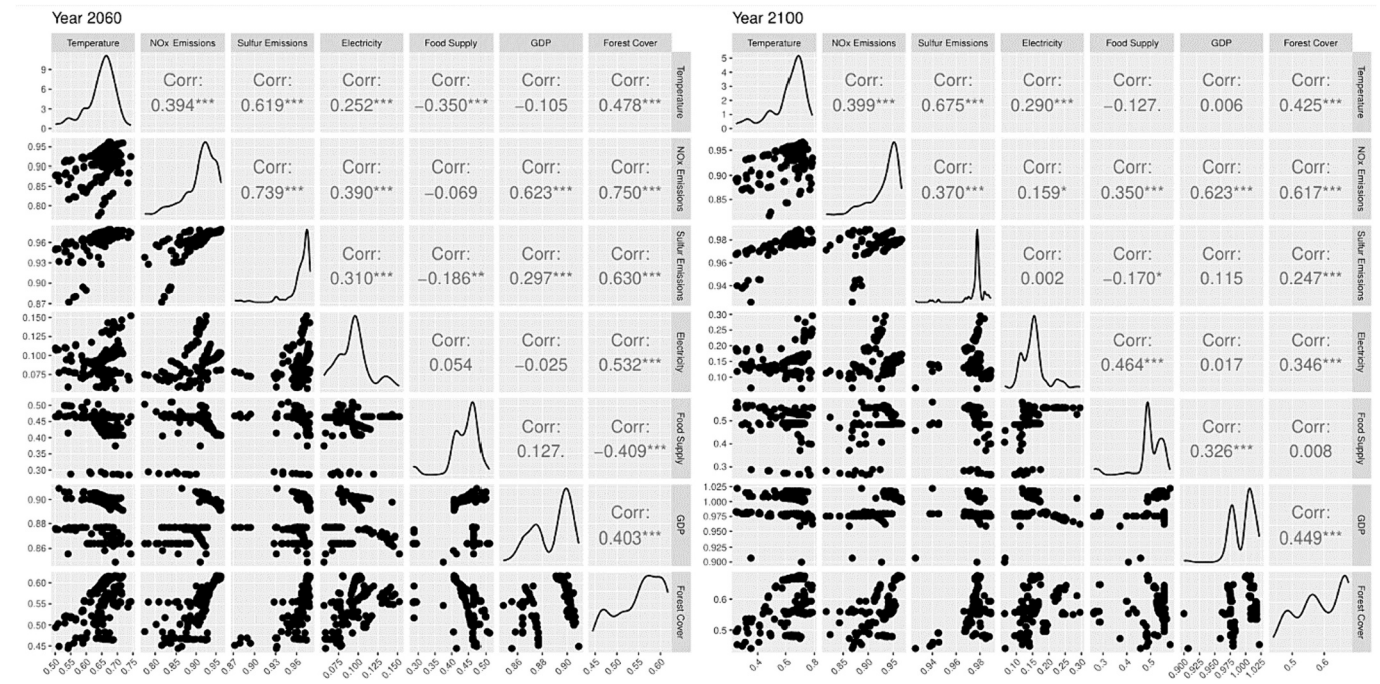


Fig. 9. Correlation matrix between indicators displayed in Fig. 2; **** if the p-value is <0.001, *** if the p-value is <0.01, ** if the p-value is <0.05, * if the p-value is <0.10, "" otherwise.

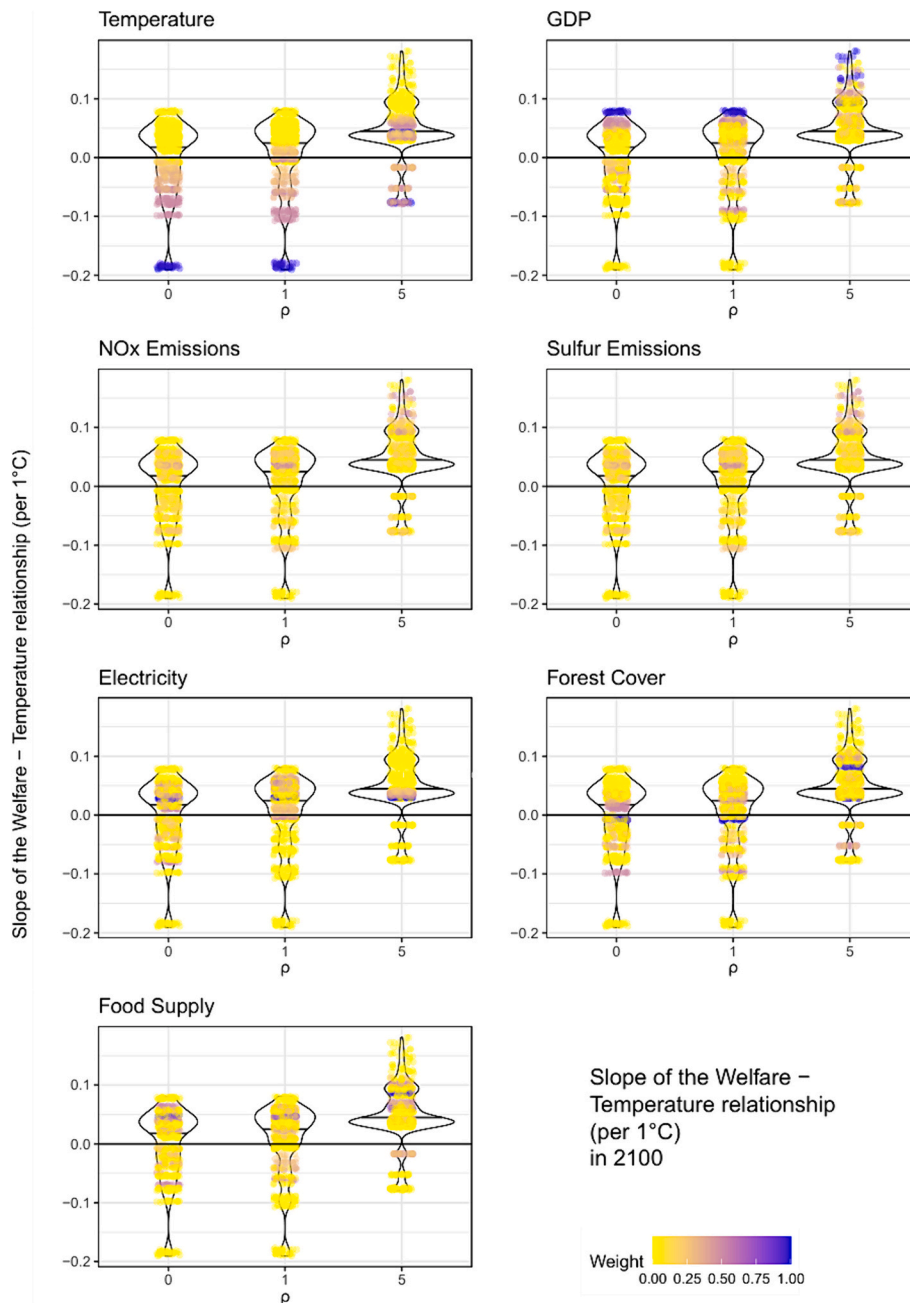


Fig. 10. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2100, for all combinations of weights and ρ . The different plots show by color the weights of each variable.

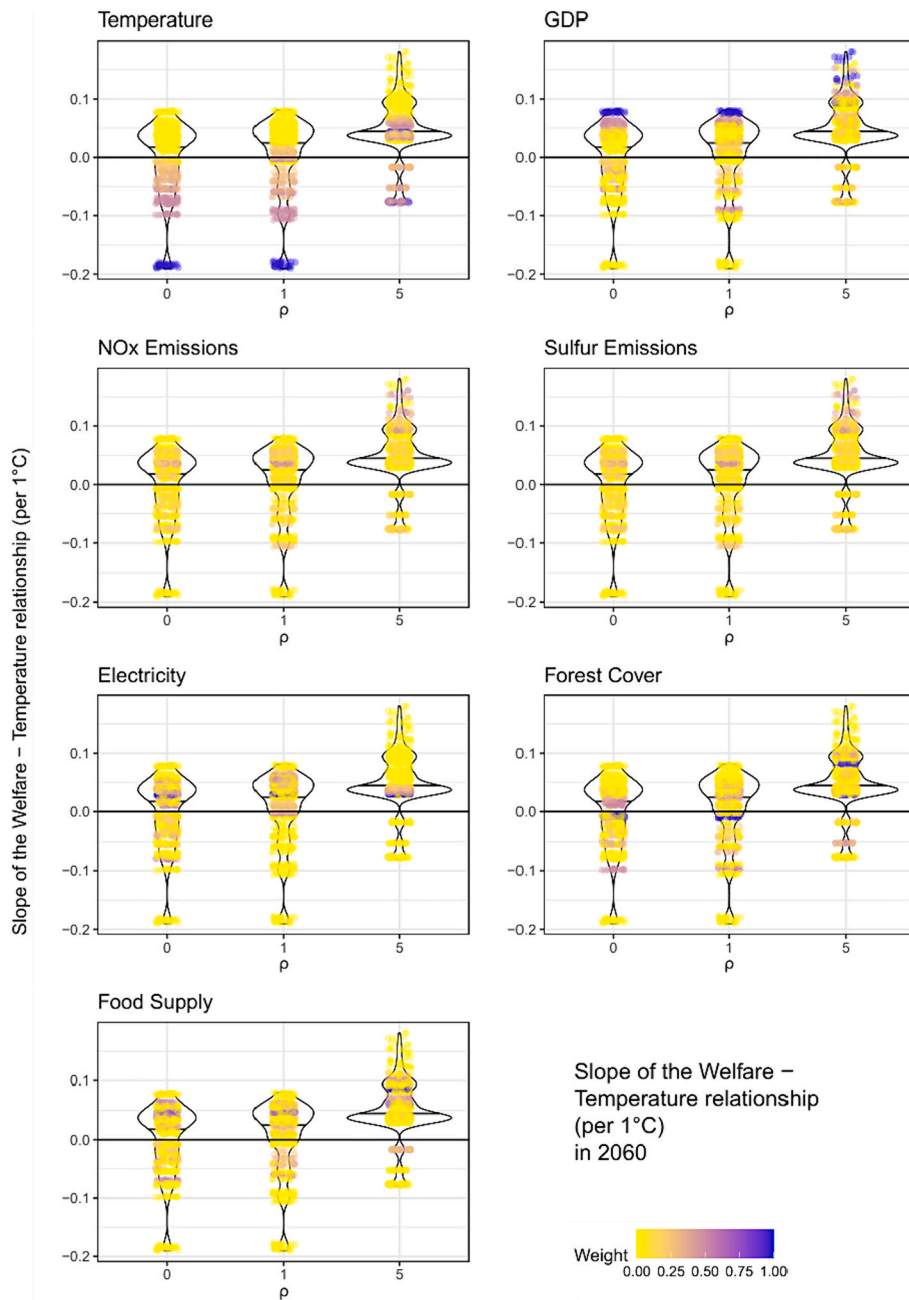


Fig. 11. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2060, for all combinations of weights and ρ . The different plots show by color the weights of each variable.

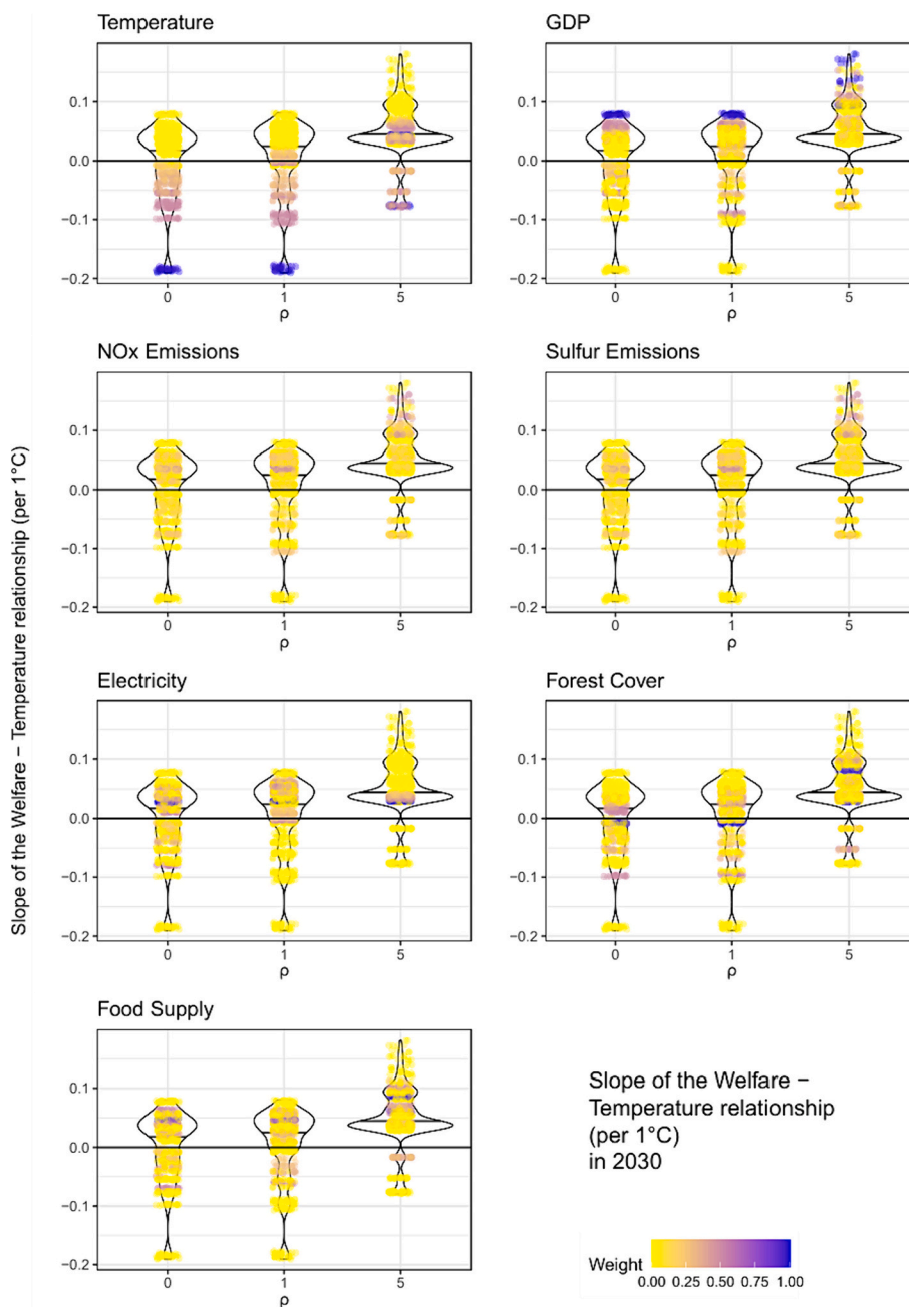


Fig. 12. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2030, for all combinations of weights and ρ . The different plots show by color the weights of each variable.

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