

**Enabling assessment of distributive justice through models for climate change planning
A review of recent advances and a research agenda**

Jafino, Bramka Arga; Kwakkel, Jan H.; Taebi, Behnam

DOI

[10.1002/wcc.721](https://doi.org/10.1002/wcc.721)

Publication date

2021

Document Version

Final published version

Published in

Wiley Interdisciplinary Reviews: Climate Change

Citation (APA)

Jafino, B. A., Kwakkel, J. H., & Taebi, B. (2021). Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *Wiley Interdisciplinary Reviews: Climate Change*, 12(4), Article e721. <https://doi.org/10.1002/wcc.721>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

ADVANCED REVIEW

WILEY

Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda

Bramka Arga Jafino¹ | **Jan H. Kwakkel**¹ | **Behnam Taebi**²

¹Department of Multi-Actor Systems, Faculty of Technology, Policy, and Management, Delft University of Technology, Delft, The Netherlands

²Department of Values, Technology & Innovation, Faculty of Technology, Policy, and Management, Delft University of Technology, Delft, The Netherlands

Correspondence

Bramka Arga Jafino, Multi-Actor Systems, Delft University of Technology, Delft, Netherlands.

Email: b.a.jafino@tudelft.nl

Edited by Mike Hulme, Editor-in-Chief

Abstract

Models for supporting climate adaptation and mitigation planning, mostly in the form of Integrated Assessment Models, are poorly equipped for aiding questions related to fairness of adaptation and mitigation strategies, because they often disregard distributional outcomes. When evaluating policies using such models, the costs and benefits are typically aggregated across all actors in the system, and over the entire planning horizon. While a policy may be beneficial when considering the aggregate outcome, it can be harmful to some people, somewhere, at some point in time. The practice of aggregating over all actors and over time thus gives rise to problems of justice; it could also exacerbate existing injustices. While the literature discusses some of these injustices in ad-hoc and case specific manner, a systematic approach for considering distributive justice in model-based climate change planning is lacking. This study aims to fill this gap by proposing 11 requirements that an Integrated Assessment Model should meet in order to enable the assessment of distributive justice in climate mitigation and adaptation policies. We derive the requirements from various ethical imperatives stemming from the theory of distributive justice. More specifically, we consider both intra-generational (among people within one generation) and intergenerational (between generations) distributive justice. We investigate to what extent the 11 requirements are being met in recent model-based climate planning studies, and highlight several directions for future research to advance the accounting for distributive justice in model-based support for climate change planning.

This article is categorized under:

Climate, Nature, and Ethics > Climate Change and Global Justice

KEYWORDS

adaptation and mitigation, distributive justice, integrated assessment model, planning, requirements

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2021 The Authors. *WIREs Climate Change* published by Wiley Periodicals LLC.

1 | INTRODUCTION

Due to the complexity of climate planning and the presence of uncertainties, understanding the implications of alternative policies under different futures is becoming increasingly relevant to policy makers. Numerical models, mostly in the form of integrated assessment models (IAMs), are among the most commonly used tools for this purpose (Patt et al., 2010; Sarofim & Reilly, 2011). Recent IPCC reports show that the evaluation of adaptation and mitigation policies through IAMs is often done from an aggregated perspective (Kolstad et al., 2014). Models aggregate costs and benefits of policies across an entire area, over all actors, and over the entire planning horizon. The reliance on this aggregated perspective is seen as one of the deficiencies of using IAMs (Stanton et al., 2009), because it obfuscates the distribution of burdens and benefits for different actors across different time and space. This gives rise to an inherent problem of justice; while a plan might be beneficial in the aggregate, its distribution of benefits and costs can give rise to injustices. These injustices, especially when not identified and accounted for in public policy, could give rise to contestations resulting in policy deadlocks (Klinsky et al., 2017; Pesch et al., 2017).

There are several reasons why justice is crucial in planning for climate change. First, the physical processes of climate change vary in space and time and have different impacts on different people (Green, 2016). Second, people's vulnerability to these impacts, their capacity to adapt, and their historical contribution to climate change are often unequally distributed (Füßel, 2010a; Thomas et al., 2019). Third, options for mitigation and adaptation to climate change are likely to unevenly affect different groups, giving rise to unjust distributions of costs and benefits, and sometimes even exacerbating existing injustices (Atteridge & Remling, 2018). Fourth, power inequalities between the well-off and worse-off groups in society tend to favor allocation of more resources to the well-off at the expense of the worse-off; this could reinforce the previous three instances of injustice (Thomas & Warner, 2019). As a result, researchers have turned to theories of justice in order to address these concerns in climate change planning.

IAMs can be better equipped to address justice concerns in climate change planning, especially in assessing the distributional outcomes of alternative policies. There are already some examples of model-based studies that allow for ad-hoc justice evaluation in recent years (see e.g., Aerts et al. (2018); Ciullo et al. (2020); Gold et al. (2019); Li et al. (2018); Van Ruijven et al. (2015)). For example, in the agricultural sector, Thornton et al. (2010) simulate the distributional impacts of climate change on agricultural productivity in East Africa in order to identify winners and losers among countries. In the electricity sector, Rao (2013) evaluates the distributional impacts of low-carbon electric supply expansion in India, especially by comparing the trade-offs between overall welfare gains and income inequality among households from different income groups. These examples exemplify the partial efforts to incorporate justice in IAMs. Each study focuses on a specific aspect of justice, operationalizes it, and develops a model in light of this specific aspect. Consequently, the way justice is addressed in these studies is case specific and not directly transferable to other cases and contexts. A systematic understanding of how to facilitate the evaluation of justice in climate mitigation and adaptation policies through the use of IAMs, based on theories of justice, is currently missing.

In this review, we contribute to the development of a systematic understanding of how IAMs can be used to facilitate the evaluation of justice in planning for climate change, especially by considering the potential injustices that aggregation gives rise to. Within the climate justice literature, it is common to make a distinction between distributive and procedural justice (Gardiner, 2010; Wood et al., 2018). Distributive justice is concerned with how outcomes are distributed across people and whether a distribution is morally acceptable (Konow, 2001; Vermunt & Törnblom, 1996). Procedural justice is concerned with fairness in and legitimacy of planning and decision-making processes (Okereke, 2010; Törnblom & Vermunt, 1999). Since we are focusing on how the results produced by IAMs can foster the evaluation of the distributional outcomes of mitigation and adaptation policies, in the remainder we will only consider distributive justice issues.

IAMs come in many guises, are used for many different purposes, and for a wide variety of decision making and planning problems at different levels of government. To help structure the wide variety of IAMs used in practice, various classifications have been proposed (Beck & Krueger, 2016; Füßel, 2010b; Kelly et al., 2013; Stanton et al., 2009). Based on the models' purposes, IAMs can be categorized into those focusing on mitigation, adaptation, and impacts assessment. Based on the way in which policies are assessed, IAMs are categorized into optimization and simulation models, although in recent years there is a growing interest in simulation-optimization IAMs as well (Dittrich et al., 2016; Moallemi et al., 2020). While optimization-based IAMs are normally used in mitigation planning, simulation-based IAMs are more often used in adaptation planning. IAMs can also be categorized based on their geographical scope, ranging from the global to local level. Rather than focusing on a specific type of IAM (e.g., based on purpose, how policies are assessed, or the geographical scope), our discussion on model-supported justice assessment is

generic enough to be applicable to a broad range of IAMs. In the remainder of this paper, we use the term IAM to refer to models used for supporting planning and decision-making for climate change adaptation and mitigation.

Our study comprises three steps. First, by systematically identifying ethical imperatives from conceptions of intra- and intergenerational distributive justice, we propose modeling requirements for enabling evaluation of distributive justice in alternative policies by using IAMs. Given that there are multiplicity of justice principles (e.g., equality, fairness, equity) that are relevant in different contexts (Van Hootegeem et al., 2020); our intention is not to build preferences toward particular principles of justice, but rather facilitating, enabling and accommodating justice debates on the basis of model-based analyses. Therefore, the systematic requirements we present in this paper are a starting point, rather than an ultimate list, for improving the assessment of distributive justice in climate change planning through the use of model-based support tools. Second, we review recent attempts at meeting these requirements. Third, we propose a research agenda based on those requirements on which advances so far have been limited.

2 | JUSTICE IN CLIMATE CHANGE

Theories of justice are rooted in ethics and political philosophy (Kolstad et al., 2014; Kymlicka, 2002). Justice in climate change was initially raised in the context of responsibilities for greenhouse gas (GHG) reductions. These responsibilities could be based on countries' past emissions (based on the principle of "you-broke-it-you-fix-it"), their ability to bear mitigation cost (i.e., capacity determines responsibility) but also future forecasts of GHG emissions (Okereke, 2010; Posner & Weisbach, 2010; Singer, 2002). Recent debates have broadened the domain of climate justice to issues pertaining to equity measurement of adaptation success, distribution of funding and resources for adaptation, and trade-offs between mitigation and adaptation (Byskov et al., 2019; Gardiner, 2010; Grasso, 2007; Klinsky et al., 2017; Paavola & Adger, 2006; Pelling & Garschagen, 2019).

Discussions about justice are usually divided into two main categories of procedural and distributive justice. Procedural justice is about the conditions under which a decision has been reached and it is concerned with fairness in planning and decision making processes (Törnblom & Vermunt, 1999). In a climate change context, procedural justice is often measured by the degree of recognition, participation, and transparency in the decision making process (Schlosberg, 2009). Distributive justice refers to the benefits and risks of activities and how those have been distributed (Caney, 2005; Konow, 2001). Indeed, procedural justice is important in climate change decision-making, both at the international level and within a country. Furthermore, procedural and distributive justice are somewhat connected. That is, power inequalities could result in an unfair allocation of resources and give rise to inequalities and exacerbate the existing inequalities (Thomas et al., 2019; Thomas & Warner, 2019). As we mentioned in the introduction, this is one of the reasons that justice needs to be explicitly addressed in climate planning. However, since the focus of the current paper is on how the results produced by IAMs can affect the distributions of burdens and benefits (and how to evaluate the ensuing justice issues), we will only consider distributive justice here. Procedural justice matters in our argument, in so far as it affects distributive issues, as they will be reflected in the IAMs.

The central goal of distributive justice is to ensure that risks and benefits are distributed in a just manner.¹ There are three central questions in distributive justice, namely what is the shape, unit, and scope of distribution (Bell, 2004; Page, 2007). In other words, which patterns of distribution do we prefer (shape), what is it that is being distributed (unit) and to whom does this distribution relate (scope). Regarding the shape, different distributional principles could be followed (Konow, 2003). A utilitarian principle, for instance, would prescribe a distribution that could maximize the utility of all, while a Rawlsian model of distribution would aim to help the least well off (Taebi, 2019). The unit question, or the question as to what it is that we wish to distribute, could be answered in different ways too. Models often discuss the distribution of some kind of value, such as economic, values, biodiversity, social values or welfare. Indeed, a fair distribution of negative outcomes such as vulnerabilities are also important. Both the shape and the unit questions become more complex when we consider the question of scope or, to whom this distribution relates, both in the spatial (intra-generational) and temporal (intergenerational) sense. This becomes particularly intricate when we need to consider temporal distribution and the associated intergenerational justice questions. What is it that we can pass on to future generations, to which future generations do we pass on these units, and what is the moral justification for that (Campos, 2018; Kermisch & Taebi, 2017; Page, 1999).

IAMs often focus on the aggregation of the outcome, either in a mathematical optimization form, or as utility aggregation of all actors across the entire time horizon (Beck & Krueger, 2016; Kolstad et al., 2014). This view in modeling, and more generally in the assessment of public policies, stems from consequentialist ethics. According to

consequentialist theories, one should assess whether good consequences of an action outweigh the bad ones. Utilitarianism, a specific form of consequentialism, is most influential in public policy (Meinard & Tsoukiàs, 2019; Posner, 1979). Utilitarians aggregate positive and negative consequences in their *calculus* and they assess the rightness of an action in terms of whether it manages to maximize utility. The aim of the modeling exercise is then to look for alternative policies that maximize this aggregated utility. For two reasons, utilitarianism is highly influential in assessing public policy (Dennig, 2017; Thaler & Hartmann, 2016): it focuses on the aggregate outcome for everybody, and it is based on the premise of fundamental equality in that everybody counts for one and no more than one in the calculations. The utilitarian calculus is blind to people's standing, status, income, race, and so on; it presumes a similar utility function (i.e., value judgments about welfare changes associated with changes in income [or other indicators]) for all individuals. Ironically, it is the same fundamental equality principle that causes a blind spot for utilitarianism. That is, the distributions of burdens and benefits are not accounted for; all that matters for the evaluation is the aggregation of total outcomes.

Distributive justice matters to IAMs in the spatial and temporal sense. Temporally speaking, we need to consider what levels of burdens and benefits are being projected into the future (and which futures); this is called intergenerational justice. This involves, among others, determining the level of preference given to impacts occurring in the far future, relative to those occurring in the present time or the near future. In climate change planning, this is typically done through discounting methods (Caney, 2009; Fleurbaey et al., 2014). Most studies related to intergenerational justice in policy appraisal investigate what the appropriate discount rate are, taking into account the societal and ethical aspects of decisions (Broome, 1992; Davidson, 2015; Heilmann, 2017).

Spatially speaking, it is important to understand how burdens and benefits are being distributed among the currently living generation; this is referred to as intra-generational justice. It distinguishes the subjects of distribution based on their attributes, for instance in how each country contributes to international mitigation efforts (Grubb, 1995; Heyward, 2007). Intra-generational justice has been at the heart of the developments of the Kyoto Protocol and the underlying United Nations Framework Convention on Climate Change. Intra-generational justice partitions a population based on either their economic conditions (e.g., poor, middle, and rich income households: Krey, 2014; Sayers et al., 2018), locations (e.g., between different cities in a region: Trindade et al., 2017), social background (e.g., between men and women in the northern and southern hemisphere; Arora-Jonsson, 2011), or means of economic livelihoods (e.g., between rice farmers, fruit farmers, and vegetable farmers in the Vietnam Mekong Delta; Smajgl et al., 2015).

3 | REQUIREMENTS FOR INCORPORATING JUSTICE IN MODEL-BASED CLIMATE PLANNING

We develop requirements to enabling justice reasoning in model-based support for climate adaptation and mitigation planning. We systematically derive the requirements by identifying ethical imperatives from the three elements of distributive justice, referring to the unit, scope or shape of the distribution. In the context of model-based planning for climate change, a first critical step is to clearly delineate the people that might be affected by the alternative policies (i.e., the *scope*). Once they have been clearly identified, a subsequent step is to consider the values that they uphold that might be affected by the policies (i.e., the *unit*) and to determine an appropriate distribution of these values across the people (i.e., the *shape*). We therefore take the scope of the distribution as our point of departure. We specifically start from theories on intra-generational and intergenerational justice.

We use the XLRM framework (see Figure 1), a commonly used framework for structuring information in model-based decision support (Kwakkel, 2017; Lempert et al., 2003), to derive the requirements. The XLRM framework

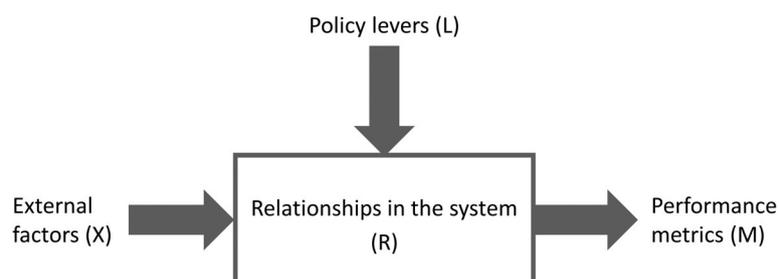


FIGURE 1 The XLRM framework for model-based policy analysis

consists of four elements. The first element is the external factors (“X”). These are mainly uncertainties that affect the system but are outside the control of policy makers. The policy levers (“L”) are interventions, in our case mitigation and adaptation policies, to be evaluated by the model. The relationships in the system (“R”) refer to model structure and features. The performance metrics (“M”) are outcome variables to be observed. We propose ethical imperatives, based on intra- and intergenerational justice, for elements within the XLRM framework. Based on the ethical imperatives, we derive 11 requirements to allow for justice evaluation as summarized in Table 1. Note that these requirements

TABLE 1 Requirements to enable the evaluation of distributive justice in model-based support for climate planning

Domains of justice in IAMs	Dimensions of justice	Ethical imperatives	Requirements	Extensiveness of application/discussion in literature
Performance metrics/indicators (M)	Intra-generational	Fair representation of actors (including acknowledgement of differentiated capacity, historical burdens and responsibility, values, and behavior) and fair assessment of distribution of outcomes	1.1 Actor-based disaggregated metrics	Many IAMs have considered this.
			1.2 Value-based disaggregated metrics	Some domain specific IAMs (such as flood risk management) still focus only on one value. Some IAMs (such as nexus-based study) have considered multiple values.
	1.3 Postprocessing of actor- and value-based metrics to account for distributive principles		State-of-the-art approaches for this are found only in a very limited number of studies.	
	Intergenerational		1.4 Time-series metrics	Most model-based climate planning have considered multi-temporal dimension, and thus time-series metrics.
			1.5 Postprocessing of time-series metrics to account for distributive principles	Discounting method based on the Ramsey's equation is widely adopted. Attempts to use other discounting alternatives are very limited.
Relationships in the system/model structure (R)	Intra-generational		2.1 Disaggregated representation of actors and values	Many IAMs have attempted in having a more disaggregated representation of the system.
	Intergenerational		2.2 Multi-temporal dimension	Most model-based climate planning have considered multi-temporal dimension, some domain specific models are not multi-temporal.
Policy levers (L)	Intra-generational	Differentiated social vulnerability	3.1 Actor-differentiated policies	Still fairly limited. Policies are usually targeted to all actors.
	Intergenerational	Freedom of choice	3.2 Assessing changes in policy space over time	Still fairly limited. Policy space is assumed to be unchanged for the entire planning horizon.
Exogenous uncertainties (X)	Intra-generational	Transparency of justice preferences	4.1 Using different distributive moral principles to account for normative uncertainties	Very limited. Utilitarian is often implicitly assumed. Few studies explicitly state this assumption and test the implications of adopting different principles.
	Intergenerational	Fair representation of actors	4.2 Exploring plausible uncertain changes in actors' behaviors and preferences/values	Very limited. Actors behaviors and preferences are assumed to be static over time.

operate on individual models. In practice, there might be flow of justice assumptions from one model to another; for instance, when some of the inputs to a given model are derived from the results of other models. In the subsequent subsections, we organize the discussion by first presenting requirements related to intra-generational justice (requirement 1.1–1.3, 2.1, 3.1, and 4.1) and then requirements related to intergenerational justice (requirement 1.4–1.5, 2.2, 3.2, and 4.2).

3.1 | Requirements from intra-generational justice

Accounting for intra-generational justice means acknowledging all actors who are affected by the climate planning problem as well as the existing injustice among them, and assessing the distribution of impacts between them on the basis of fairness. To realize these imperatives, one has to first understand the properties of the climate planning problem for which the model is being used. We propose two properties as relevant. The first property relates to a typology of actor representation as illustrated in Figure 2. The ethical imperative of fair representation of actors implies that the model structure of IAMs should allow for justice assessment among values, that is, the *unit* of the distribution (requirement 1.2, e.g., balance between impacts to economic and environment) and assessment of the distribution of these values between actors, that is, the *scope* of the distribution (requirement 1.1, e.g., economics performance across different districts). Some IAMs, however, combine diverse actors into a single representative agent and consider only a single value. Such model structures can be found in many IAM categories ranging from optimization-based IAMs for global mitigation (de Bruin et al., 2009; Nordhaus & Boyer, 2000) to simulation-based IAMs for local adaptation (Gohari et al., 2017; Hidayatno et al., 2017). In other studies, multiple actors are already explicitly represented and multiple values are also evaluated (Conway et al., 2015; Manne & Richels, 2005).

The second property of climate planning problems relates to how policies are designed and evaluated. Broadly speaking, there are two approaches (Beck & Krueger, 2016; Herman et al., 2015): having a set of prespecified alternative policies or using optimization to design policies. The way in which policies are generated affects how the distribution of outcomes is treated (requirement 1.3). If policies are prespecified, which is the case for most simulation-based IAMs, the function of IAMs is to rank policies based on their performance. Accordingly, evaluation of justice can only be performed a posteriori, that is, after the performance of the policies has been calculated. This requires postprocessing of performance metrics, either by aggregating them into a single composite indicator (Chung & Lee, 2009; Luis et al., 2019), or by keeping them separate and evaluating trade-offs among them (Garner et al., 2016; Haasnoot et al., 2012). If policies are found through optimization, evaluation of justice can be included not only a posteriori, but also a priori in how the optimization problem is formulated (Ciullo et al., 2020; Gourevitch et al., 2020; Wild et al., 2019).

Explicitly specifying performance metrics for multiple actors and for diverse values implies two additional requirements (both encapsulated in requirement 2.1). First, in order to ensure a just representation of actors, one has to understand the heterogeneity of actors' background and behaviors, and accordingly represent this heterogeneity in the model. For instance, in models used to support adaptation planning for farmers, one has to specify the economic (e.g., small-, medium-, or large-scale) and social background (e.g., traditional and risk-averse, or modern and risk-taker) of the farmers, and identify the heterogeneity of the farmers' behaviors depending on their background. Accounting for heterogeneity is also useful for addressing corrective and compensatory justice (Ikeme, 2003; Page & Heyward, 2016), for instance by incorporating historical emission accountability or harm already done by climate impacts, although efforts to do so are only recently growing (Schinko et al., 2019). The second requirement is that the model has to be able

	Single value	Multiple values
Single actor	No consideration of justice	Justice across values
Multi-actor	Justice among actors	Justice among actors, across values

FIGURE 2 Typology of actor representation in model-based support for climate planning

to quantify the diverse values that the different actors cherish (e.g., economic, biodiversity, and social). This entails including multiple subsystems and hence the corresponding cross-sectoral interactions between them (Harrison et al., 2016; Verburg et al., 2016).

The design and evaluation procedure of alternative policies induces two further requirements. The first requirement is related to the subject of the policies (requirement 3.1). A policy can be designed to target either all actors simultaneously (García-Muros et al., 2017) or only some specific actors (Fell & Linn, 2013; Mérel & Wimberger, 2012). From a justice point of view, as is the case in the broader climate justice discussion (Grasso, 2010), it is imperative to treat each actor differently based on his/her capability and vulnerability, and (historical) injustices among them. However, from a model-based policy analysis point of view, actor-specific policies and optimization for individual actors could lead to unintended consequences where a policy applied to one actor induces detrimental impacts to other actors (Ciullo et al., 2019; Fowlie & Muller, 2013).

The second requirement is related to the reflection on the distributive moral principles, that is, the *shape* of the distribution, used to assess the distribution of the disaggregated metrics (requirement 4.1). When aggregating multiple performance metrics, or embedding them in an optimization problem, certain moral principles are (implicitly) used, such as utilitarian-based maximization of overall welfare (Eijgenraam et al., 2016; Sáez & Requena, 2007), egalitarian-based equalization of costs and benefits to all actors (Ciullo et al., 2020), or Rawls' difference principle of improvement for the least well-off (Dennig et al., 2015; Gold et al., 2019; Gourevitch et al., 2020). The implicit adoption of a moral principle conceals the social justice preferences of the modelers and thus reduces the transparency of the model. Furthermore, social justice preferences are specific in space, time, and contexts (Bell, 1993; Lau et al., 2021; Van Hootegeem et al., 2020).

The diversity of moral principles can become a source of contestation among stakeholders (Hulme, 2009; Okereke, 2010). This is particularly evident in studies that use IAMs for supporting mitigation planning. Here, the choice of the guiding principles in allocating mitigation budgets and in calculating aggregate welfare strongly affects the distributional outcomes across nations (Adler et al., 2017; Höhne et al., 2014; Peters et al., 2015; Robiou du Pont et al., 2017). Shifting from people-based equity allocation to “blended” sharing principles, for instance, implies a reduction of the required mitigation rate by around 60% for North American countries, while increasing it by almost 50% for African countries (Raupach et al., 2014). In this domain, the arbitrary use of certain distributive principles without proper ethical justification has been criticized (Kartha et al., 2018). The diverse preferences of moral principles are also a manifestation of ethical uncertainty, as different moral principles illuminate different ethical issues at stake (Taebi et al., 2020). Hence, it is useful to simultaneously explore multiple moral principles when comparing alternative policies.

3.2 | Requirements from intergenerational justice

We identify five requirements grounded in intergenerational justice. The first two requirements are rooted in the imperatives of the fair representation of future generations and the fair assessment of the distribution of impacts on them, as well as fair accounting of past injustices to address corrective and compensatory justice. The two requirements are the disaggregation of performance metrics across time and the postprocessing of such time-series metrics (requirement 1.4 and 1.5). Discounting methods are often used to aggregate time-series metrics by weighing impacts that occur in the future in comparison to impacts that occur now (Heal, 1997).

As for the third requirement, in order to output time-series metrics, the model needs to have a temporal dimension, so that impacts can be observed over time (requirement 2.2). Many climate mitigation IAMs on global and national scales are already multi-temporal in nature (Nordhaus & Boyer, 2000; Popp, 2004; Stehfest et al., 2014). Conversely, many simulation-based IAMs for local scale adaptation, such as those in the domains of flood risk management (Hsu et al., 2011; Triet et al., 2018) and agricultural management (Audsley et al., 2008; Münier et al., 2004), are often not multi-temporal. This does not necessarily mean that they cannot be used for calculating impacts across time. Such models can be run in a multi-temporal fashion. For instance, an inundation model can be run for multiple points in time in the future so that the model can still produce intertemporal outcomes.

The fourth requirement relates to policy lock-ins and lock-outs and how this reduces the set of possible policies available to future generations (requirement 3.2). This requirement stems from a moral duty to promote intergenerational freedom of choices, that is, preserving the range of choices that future generations would still have to pursue a good life (Barry, 1997; Karnein, 2015). In climate change planning, the choice of implementing certain interventions at a particular point in time in combination with the unfolding exogenous changes may create lock-ins

that prevent the execution of other interventions in the future (Haasnoot et al., 2020; Savini et al., 2015). Furthermore, some policies such as infrastructure development, are largely irreversible, although the degree to which irreversibility is acceptable is subject to ethical questions (Barry, 1997). Model-based support for climate planning often focuses solely on the outcomes calculated by the model while disregarding the potential lock-ins arising from those actions (Haasnoot et al., 2019). On an abstract level, it is worth noting that value judgments still need to be made in determining how much and what kind of freedom we should leave for future generations.

The fifth requirement arises from the fact that we do not know the values that future generations will uphold. Hence, in order to have a fair representation of future generations, we need to explore plausible value changes (requirements 4.2). As argued by Padilla (2002) and Taebi et al. (2020), accounting for intergenerational justice requires one to acknowledge that the values of the current generation cannot simply be assumed to also hold for future generations. Furthermore, the values that people uphold in turn influence how they behave under different circumstances (Ajzen, 1991). For example, if we look at the evolution of water management practices in the Dutch delta, we see that in the early 20th century flood safety was the sole objective. This started to change in late 1960s, when ecological damages resulting from dams closing made environmental concerns an additional objective of the water management (Correljé & Broekmans, 2015). In addition to uncertainties pertaining social aims of future generations, there also exists uncertainties in what distributive principles future generations will prefer—coined as evolutionary normative uncertainties (Taebi et al., 2020).

4 | RECENT PRACTICES IN INCORPORATING JUSTICE IN MODEL-BASED CLIMATE PLANNING

In this section we review the degree to which the various requirements are being addressed in recent model-based climate planning studies. We conducted the review by looking at how recent IAMs from various scales, domains, purposes, and use-cases are meeting the requirements. We complemented this with requirements-specific keywords search, such as “discounting” for the postprocessing of time series metrics requirement (requirement 1.5), in order to find seminal publications. We then applied a snowball literature review approach starting from the seminal publications. Requirements related to performance metrics (“M” in Table 1) and model structure (“R” in Table 1) are increasingly being met.

4.1 | Disaggregation of performance metrics and systems representation

Requirements 1.1, 1.2, and 2.1 relate to the disaggregation of actors and values. One of the earliest efforts to disaggregate the representative agent assumption is in IAMs used for cost–benefit analysis in mitigation planning. The RICE model modifies the DICE model by dividing the world into 10 different regions (Nordhaus & Yang, 1996). This study was controversial as it revealed that high-income countries would be the main losers from cooperative policies. Later, it was found that this emerged because RICE was using the same diminishing marginal returns to income for all regions (Aronsson et al., 2010; Stanton, 2011). This makes shifting income from richer regions to poorer ones a preferable policy, as this increases total welfare. Furthermore, spatial disaggregation of actors in global IAMs also entail formulating regionally differentiated climate damage functions (Diaz & Moore, 2017; Nordhaus, 2014), the use of which is still subject to ethical criticisms (Pezzey, 2019; Pindyck, 2017). This illustrates the nontriviality of disaggregating the representation of actors within a model.

Twenty years after the RICE study, the importance of disaggregating performance metrics and actor representation is again emphasized by IAMs in various categories. In the local adaptation domain, Aerts et al. (2018) distinguish agents in flood risk assessment based on their economic, social, geographic, and cultural background. Such distinctions are important for assessing distributional impacts as well as having a better representation of people's behavior to flood risk. To represent values heterogeneity, a regional adaptation simulation model developed by Harrison et al. (2016) explicitly considers cross-sectoral interactions between different domains in order to calculate 14 metrics of climate impacts on different values a society cherishes. The system dynamics modeling formalism has also been widely used for such multi-value analysis both for global mitigation and local adaptation purposes (Agusdinata, 2008; D'Alessandro et al., 2020; Walsh et al., 2017), especially due to the straightforwardness of constructing feedbacks among distinctive variables (Akhtar et al., 2013; Kelly et al., 2013). A systems-of-systems and coupled components modeling framework

has also been proposed for accounting for multi-value multi-sector studies (Little et al., 2019). Red flags about such a framework, however, have been raised due to the potential technical and conceptual misalignments when one starts to couple models from different paradigms (Voinov & Shugart, 2013).

Rao et al. (2017) summarize the challenge of disaggregation of system representation and performance metrics, with a focus on IAMs used for supporting mitigation planning. They discuss state of the art practices for such disaggregation and future research directions to improve model outputs and model features. In line with the requirements proposed in this study, they suggest that in the future, outputs of models used for supporting climate change planning should consider multi-dimensional indicators and distributional impacts. To realize this, the model structure should reflect heterogeneity of household groups and sectoral impacts.

4.2 | Postprocessing for intra-generational justice

Disaggregating performance metrics results in a substantially higher number of metrics to be evaluated. There are two approaches for appraising high dimensional model outputs (requirement 1.3): calculating composite indicators or keeping the metrics separate. The first approach imposes an aggregation function on multiple performance metrics in order to transform them into a single overarching metric (Sikdar, 2009). Aggregation functions derived from welfare theory, so called social welfare functions (SWFs), are often used especially in IAMs for mitigation planning and burden sharing (Adler et al., 2017; Botzen & van den Bergh, 2014; Fankhauser et al., 1997). One of the most widely used SWFs is the utilitarian welfare function (Millner, 2013). This is an additive function where one performs linear aggregation across the utility of all individuals. Other SWFs, such as the Bernoulli–Nash (Cobb–Douglas) welfare function, have a multiplicative property instead.

It has been argued that both the utilitarian and Bernoulli–Nash SWFs neglect equity and fairness, as they aim to maximize the total welfare while ignoring its distribution (Tol, 2001; Tol et al., 2004). Equity weighting functions have been proposed to overcome this limitation (Anthoff et al., 2009; Hope, 2008). An example of an equity weighting SWF is the Negishi welfare function (Stanton, 2011), which attaches equity weights to individuals inversely proportional to their marginal utility of consumption. Adler et al. (2017) introduce the prioritarian SWF, where the original utility of individuals is transformed using a strictly increasing and concave function, thus giving more weight to the increase in utility of worse-off individuals. Different composite indicators can also be used simultaneously. For example, Huang et al. (2019) evaluate the implications of alternative carbon emissions trading systems in China by assessing the change in the aggregate household income, Gini coefficient, and the Oshima inequality index. While the use of equity weighting SWFs is prominent in global and regional optimization-based IAMs, their uptake in simulation-based IAMs is still limited (see e.g., Kind et al. (2017) for an example of the use of equity weighting functions in model-based adaptation planning). The use of composite indicators is more prevalent in simulation-based IAMs (e.g., Balica et al., 2012; Koks et al., 2015).

The second approach to deal with disaggregated metrics is by keeping them separate. This is because when using aggregation approaches, one risks having a subset of performance metrics dictating the overall performance of a policy, without knowing a priori which one will be the dictatorial metric (Franssen, 2005). Hence, some authors appeal to keeping the metrics disaggregated (Kasprzyk et al., 2016; Machado & Ratick, 2018; Watkiss, 2011). This approach is often found in simulation-based IAMs. For instance, Ahmed et al. (2017) assess the performance of alternative adaptation pathways for the western Ganges floodplain based on both their effectiveness in reducing flood risk, their impacts on economic development, and their sociopolitical feasibility. The advancement in many-objective optimization has contributed to the uptake of the disaggregated metrics approach in simulation-optimization IAMs. As an example, Trindade et al. (2017) combine both actor and value-based metrics in designing drought adaptation strategies for North Carolina. They consider the trade-offs between three different values: the reliability of water reservoir, the use of restricted water stock, and the total drought management cost, across four different water utilities (i.e., actors).

4.3 | Postprocessing for intergenerational justice

Using time-series metrics is an obvious way to represent impacts over time. However, instead of treating them as the dynamics of impacts over time, time-series metrics are often aggregated into a net present value. This is because such

an aggregation results in a complete ranking of alternative policies, making comparison between policies easier. Ramsey's social discount rate is the most popular methods for doing this (Baum & Easterling, 2010; Stanton et al., 2009). Ramsey's social discount rate contains assumptions on how to weight impacts experienced by future generations. These assumptions are susceptible to empirical and normative uncertainties (Arrow et al., 2012; Storm, 2017). The empirical uncertainties mostly relate to the assumption of the welfare growth rate of future generations. The normative uncertainties concern ethical disagreements on how future generations should be valued in present day decision-making.

The normative and empirical uncertainties associated with Ramsey's social discount rate are often disregarded both in global IAMs for supporting mitigation planning, and in local and national IAMs for adaptation planning (Ackerman et al., 2009; De Cian et al., 2018). There are a few exceptions. Arrow et al. (2014) suggest using a declining discount rate for long-term governmental projects. Heal and Millner (2013) aggregate heterogeneous discount rates from actors with different pure rate of time preferences and explore several conditions that have to be met for the approach to be morally justifiable and analytically consistent. As illustrated by these examples, innovations in discounting are mostly found in methodological-focused studies using optimization-based IAMs for setting global mitigation target. Their uptake in simulation-based IAMs for adaptation planning is still fairly low.

4.4 | Design of policies

Only recently, actor-differentiated policies are being considered in IAMs (requirement 3.1). This is mostly found in simulation-based IAMs for local adaptation that use either spatially explicit coupled components or agent-based modeling formalisms. For example, Andr ee et al. (2017) evaluate alternative subsidy schemes to support the cultivation of bio-fuel crops in the Netherlands. Rather than applying a homogenous subsidy scheme to all farmers, they propose heterogeneous subsidy schemes based on the farmers' biophysical and economic production factors. Jafino et al. (2019) evaluate the efficacy of actor-differentiated soft policies, such as zoning policies, in addition to both aggregate and actor-differentiated hard infrastructure policies in a hypothetical delta planning. Actor-differentiated policies are only recently being adopted in IAMs operating at a larger scale, as exemplified by Stiglitz (2019) who applies a heterogeneous sector-specific carbon pricing mechanism for climate mitigation.

A recent innovation regarding policy specification is the explicit consideration of path dependency (requirement 3.2). Path dependency means that the initial action shapes the set of actions available in the future. The adaptation pathways approach attempts to include a path dependency analysis, and is often being used in combination with model-based decision support tools (Haasnoot et al., 2013). The final product of this approach is an adaptation pathways map; a metro-map like overview of alternative sequences of adaptation actions that could be taken in the future conditional on how exogenous conditions unfold. Path dependency and lock-in effects could be intrinsically considered when constructing adaptation pathways, or—as inspired by the significance of measuring flexibility in strategic planning (Rosenhead, 1980; Rosenhead et al., 1972)—explicitly quantified through the concept of “transfer costs” (Haasnoot et al., 2019). The adaptation pathways approach has been predominantly used in national and local scale IAMs in water and energy domains (de Ruig et al., 2019; Michas et al., 2020; Radhakrishnan et al., 2017).

5 | FUTURE RESEARCH AGENDA

Here, we discuss three promising research directions based on requirements that have received only limited attention so far. A first research direction concerns postprocessing for intra-generational justice. Requirement 1.3 on actor specific and value-based metrics, and the related requirement 4.1 on using multiple moral principles side by side, are both concerned with enabling the making of an informed choice among different alternative policies and social justice preferences. Neither requirement has received much attention. A second research direction is the processing of time series metrics, which is fundamental for intergenerational justice (requirement 1.5). While alternative discounting methods are being discussed at a theoretical level for global mitigation IAMs, their uptake in other types of IAMs is still limited. A third research direction is the explicit consideration of uncertainties in future actors' behaviors and preferences (requirement 4.2), as most studies still assume static behavior and preferences.

5.1 | Using moral principles to process actor- and value-based metrics

The goal of postprocessing disaggregated metrics (requirement 1.3) is to evaluate policies based on certain distributive principles. The main question is how one can make an informed choice among alternative policies based on their efficacy as estimated by IAMs, whereas the efficacy is evaluated based on how the policies satisfy the diverse values the society cherish and how the distribution of the impacts looks like. This question is also at the heart of social choice theory (Suzumura, 2001): how can one combine preferences and interests of diverse individuals? Therefore, methods and techniques from social choice theory, some of which exemplified in Table 2, are useful. From Table 2 it is evident that applications of aggregation-based SWFs are mainly found in optimization-based IAMs for mitigation planning while applications of disaggregation approaches are mainly found in simulation-based IAMs for adaptation planning.

There are two challenges in adopting techniques and methods from the social choice & welfare theory. The first challenge is correctly applying multiple distributive moral principles and interpreting their relevance and policy implications (requirement 4.1). The utility-maximizing principle is the most widely used in climate planning. Other ethical principles, such as prioritarian and Rawlsian maximin, have been applied in only a few studies. There are also ethical principles that have been argued to be relevant for climate planning, but to our knowledge have never been applied in model-based climate planning studies, such as the sufficientarian SWF. It is also important to note that any welfare function makes value judgments about welfare changes associated with changes in income (or other indicators). The task of an analyst working with a computational model is not to make such value judgments, but to shed light on the ethical underpinnings behind the aggregation approaches as well as their corresponding consequences (Kartha et al., 2018).

The second challenge is selecting or developing an appropriate operationalization of the chosen moral principle for model-based support for climate planning. Any social welfare function has certain requirements and assumptions that limit the scope of its application. For example, the greatest unhappiness for the least number principle assumes “ordinally measurable and interpersonally non-comparable utilities” (Bossert & Suzumura, 2017). One has to make sure that the model outcomes and the nature of the problem do not violate the limitations posed by the social welfare function. Making these limitations and assumptions explicit and ensuring that the setup of the model-based support tools complies with the limitations of the moral principle are essential to ensure the validity of the chosen social welfare function.

5.2 | Using alternative methods for dealing with time-series metrics

There are two options related to the processing of temporally disaggregated metrics. The first one is using alternative discounting methods. Multiple alternatives to Ramsey's social discount rate have been proposed recently at a theoretical level: sustainable discounted utilitarianism, rank discounted utilitarianism, the Calvo criterion, and the Chichilnisky criterion (Asheim, 2017). Sustainable discounted utilitarianism discounts the utilities of future generations if and only if they are better off than the present generation (Asheim & Mitra, 2010). In rank discounted utilitarianism, utilities of different generations are discounted not based on the order of time of their occurrence. Rather, the utilities are first reordered based on their magnitude, and then the discount rate is applied based on this rank-ordered list (Zuber & Asheim, 2012). The Calvo criterion is built upon the maximin SWF (Calvo, 1978). It aggregates time-series metrics based on the minimum of the altruistic welfare calculated from the standard social discount rate. The Chichilnisky criterion applies a convex function to the net present utility generated by standard discounting and the limit of transformed well-being (the generalized utility).

The second option, proposed by Heilmann (2017), is abandoning discounting altogether, and going for alternative frameworks that are less vulnerable to normative uncertainties. To this end, one can draw from the disaggregation approaches as used for intra-generational justice. Specifically, one can perform an inter-temporal trade-off analysis by calculating net present values for the different generations independently. This results in having multiple net present values belonging to different generations instead of a single overarching net present value as is the case in discounting methods. By following this approach, intergenerational trade-offs can be explicitly assessed. The methodological issue to this lies in determining the time horizon of a single generation due to the transgenerational community phenomenon (Campos, 2018; Gosseries, 2008); people live not within a particular generation, but within overlapping generations that encompass others who are born earlier or later.

TABLE 2 Methods and techniques from the social choice and welfare theory that are applicable for processing disaggregated metrics

Approaches	Sub-approaches	Methods and techniques	Sources for theoretical development	Examples of applications in climate change planning
Aggregation	SWFs that have been applied	Utilitarian WF	Adler (2019); Botzen and van den Bergh (2014); Sen (2018)	Kind et al. (2017); Nordhaus (2011); Tol et al. (2004)
		Negishi weighting	Negishi (1972)	Stanton (2011); Yang and Nordhaus (2006)
		Prioritarian WF	Boadway and Bruce (1984); Parfit (2012)	Adler et al. (2017); Adler and Treich (2015); Gourevitch et al. (2020)
		Bernoulli–Nash WF	Boadway and Bruce (1984); Nguyen and Rothe (2014)	Fankhauser et al. (1997); Tol et al. (2004)
		Rawlsian maximin WF	Rawls (1974)	Botzen and van den Bergh (2014); Tol et al. (2004)
		Egalitarian WF	Kolm (1977); Pazner and Schmeidler (1978)	Dietz and Asheim (2012); Kind et al. (2017)
		Weighted utilitarian WF	Baron (1994)	-
	SWFs that have not been applied and are potentially useful	Relative egalitarian WF	Sprumont (2013)	-
		Sufficientarian WF	Shields (2012)	-
		The greatest unhappiness of the least number	Bossert and Suzumura (2017)	-
		Leximin	Barbarà and Jackson (1988)	-
		Relative utilitarian WF	Dhillon and Mertens (1999)	-
		Inequality indicators that have been applied	Gini coefficient	Gini (1936)
	Oshima inequality index		Oshima (1970)	Huang et al. (2019)
	Poverty indices		Sen (1997)	Rao (2013)
	Inequality indicators that have not been applied and are potentially useful		Generalized entropy	Cowell and Flachaire (2015)
		Mean deviation	Cowell and Flachaire (2015)	-
		Distributional dominance comparison	Cowell and Flachaire (2015)	-
		Envy measures	Bosmans and Öztürk (2018); Konow (2003)	-
Dis-aggregation	Disaggregation approaches that have been applied	Pareto optimality	Cohon and Marks (1975); Deb and Saxena (2006)	Kasprzyk et al. (2013); Kasprzyk et al. (2016)
	Disaggregation approaches that have not been applied and are potentially useful	Judgment aggregation theory	List (2012)	-

5.3 | Incorporating uncertainties in human behaviors and values preferences

A key requirement from an intergenerational perspective is guaranteeing a just representation of future generations by understanding the changes in their background, behaviors and values over time, which are uncertain by nature (requirement 4.2). This leads to two research challenges. The first one relates to the two properties of actor heterogeneity as presented in Figure 3: internalizing changes in actor group membership and actor behaviors. The relative membership proportion of each actor group refers to the distributional mix of the groups in the model (e.g., 60% poor, 30% middle-class, 10% rich agents), while the behavior is the actions and/or decision-making processes of each actor group in the model. The relative proportion and the behavior of each group can be either static or dynamic over time. When static properties are assumed, the proportion and behavior of each actor group remain unchanged for the entire simulation horizon (e.g., the distribution of poor, middle-income, and rich agents in the model remains constant at 60, 30, and 10% respectively). Conversely, dynamic properties imply that the properties may change over time. The dynamics can be represented as either exogenous (represented as uncertain forcings to the model) or endogenous (change due to internal processes within the model). This can be achieved, for instance, by drawing from theories of behavioral economics and cognitive psychology (Mathias et al., 2020; Schill et al., 2019).

Many optimization-based IAMs are located in the bottom left region of Figure 3 where, for instance, adaptation behavior is considered to be constant over time (Füßel, 2010b; Schneider & Lane, 2005). Simulation-based IAMs, especially those with explicit individual actors representation such as microsimulation and agent-based models, have to some extent dynamic-exogenous representation of group proportion (e.g., Hallegatte & Rozenberg, 2017). Moving to the top right corner of the diagram poses an ethical trade-off. Modelers have to know, or at least assume how future generations would change their behavior under different circumstances (Sondoss et al., 2020). Such a presumptuous approach might increase the epistemic uncertainties in the model (Vezér et al., 2018). The approach might underestimate the uncertainties of human behavioral systems and hence limit the potential representation of future generations.

The second research challenge is incorporating uncertainties in the future generations' values. Selection of values to be considered is inevitable in model-based support for climate planning. The selection is often grounded in the observed behavior of actors. However, as is the case with other uncertainties, there is no guarantee that the historical observation will still hold true in the future, due to the prevalence of contextual factors and shocks (Bednar et al., 2015). Value change theories provide alternative modes—such as emergence of new values, changes in relevant values, and changes in the relative importance of different values—that could be a starting point to operationalize uncertainties in future values (Demska et al., 2015; van de Poel, 2018). It is important to re-emphasize that exploration of plausible value changes is not only about what societal aims future generations will value. What distributive moral principles they will prefer and apply are also subject to uncertainties. This highlights the importance of using multiple moral principles in model-based planning for climate change.

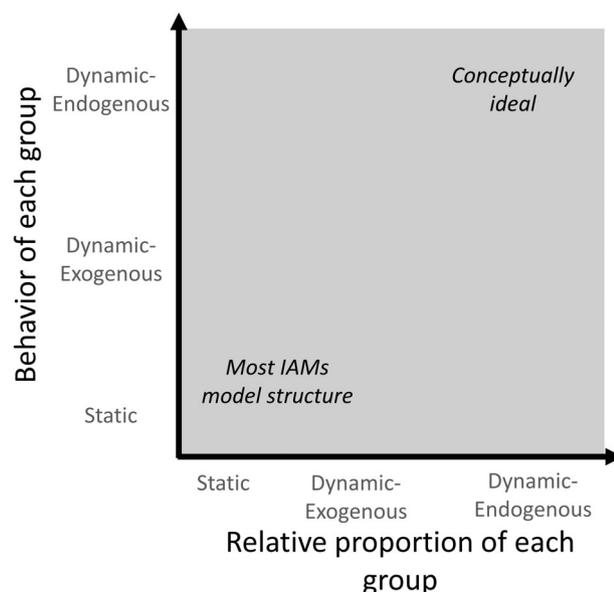


FIGURE 3 Representation of actor heterogeneity in IAMs

5.4 | Priority issues for different types of models

While pursuing the three research items above would improve our abilities for assessing distributive justice, the urgency, relevance, and difficulty of each research item differ across the different types of IAMs. The mainstreaming of alternative moral principles in simulation-based IAMs, especially those used for adaptation planning, is fairly straightforward. It is a low-hanging fruit that can yield high societal impacts as more local- and national-level adaptation planning processes are supported by such models (Palutikof et al., 2019). Similarly, the use of multiple social discount rates in IAMs for supporting mitigation planning can be a short-term priority, owing to the recent theoretical developments of alternative social discounting frameworks (Asheim, 2017). Disaggregation approaches, both in dealing with actor-based and time-series metrics, are easier to implement in simulation-based IAMs. For optimization-based IAMs, adopting disaggregation approaches requires reformulating the internal model structure into a multi-objective optimization framework. This is even more challenging for IAMs that use multiple, recursive, and/or intertemporal optimization routines in their current structure (see Keppo et al., 2021 for examples of such models). Finally, incorporating uncertainties in human behaviors and value preferences is a hard problem especially for global optimization-based IAMs. This research item is more manageable in simulation-based IAMs for supporting smaller-scale (e.g., local or national) adaptation planning, as in-depth conceptual exploration of plausible value changes can be included in for example, a participatory model building process.

6 | CONCLUSIONS

Despite the mounting evidence of the importance of including justice in climate planning, and despite advances in the complexity of model structure, the degree to which justice deliberation can be facilitated by model-based support tools is still fairly limited. Grounded in theories of justice, this review paper contributes to the literature by systematically constructing requirements for IAMs in order to allow for justice evaluation. The requirements are derived from ethical imperatives rooted in two conceptions of distributive justice, namely intra-generational (between people in the same generation) and intergenerational (between different generations) justice. Eleven requirements are proposed and structured based on the XLRM framework. This systematic operationalization of climate justice into requirements for model-based climate planning, along with a review of the degree to which these requirements are receiving attention in the literature, helps us in understanding where we stand with respect to methodically considering justice in model-based climate planning and how we can move forward.

Requirements associated with model structure (“R” in the XLRM framework) and performance metrics (“M”) have largely been satisfied. These requirements are mainly concerned with the disaggregation of system representation by accounting for different actors and different values that the actors cherish. By explicitly modeling different actors and values, modelers and planners can observe the distributive impacts of policies on each actor and value. An assessment of intra-generational justice can then be made based on a given moral principle. In addition, by using IAMs in a multi-temporal fashion, modelers and planners can observe the expected impacts to future generations.

Three directions for future research have been proposed. The first one is the (post)processing of actor- and value-based disaggregated metrics through the use of methods and techniques from the social choice and welfare theory. It is important to recognize that behind the seemingly neutral term of “postprocessing,” there exists various ethical principles that reflect what society considers to be fair distributional outcomes. The second direction is the processing of temporally disaggregated metrics. This study has presented alternative discounting methods that are currently underexplored, as well as other alternatives for dealing with time-series metrics aside from using discounting methods. The third one is incorporating uncertainties in human values and behavioral systems with a higher granularity. This can be done by making value and behavioral changes an internal process in the model, although it comes at the expense of increasing normative uncertainties. These three challenges are rooted in the need to deal with the plurality of social justice preferences and values both now and in the future.

The requirements put forward in this paper are relevant to two different bodies of literature. In the climate justice literature, hitherto, the role of IAMs has not previously been discussed as a separate domain of climate justice requiring its own sphere of discussion (Byskov et al., 2019; Gardiner, 2010). Building on Beck and Krueger (2016), we argue that many justice considerations are actually intrinsic to IAMs and therefore require specific attention. With respect to the IAM literature, many of our findings support past suggestions on how to improve the quality of IAMs (Rao et al., 2017; Schneider, 1997; Stanton et al., 2009). Past works within this body of literature, however, focused only on how the

design of the model structure and the specification of model outcomes could be improved to account for heterogeneity, and how implicit assumptions embodied within a model could be made explicit. While this, to some extent, enables evaluating distributive justice, here, we expand on this by highlighting the necessity of caring for how model outcomes should be evaluated, how policies should be designed, and what external uncertainties should be addressed.

Lastly, it is important to acknowledge that serious ethical concerns can be raised regarding whether numbers calculated by models can ever be used to meaningfully anticipate future injustices. In developing more detailed models, one needs to gather more data or make more heroic assumptions, which subjects the model to more uncertainty (Saltelli et al., 2020). In mitigation-based IAMs, for example, there are ethical controversies regarding the applicability of climate damage functions (Pezzey, 2019). This is further complicated by the presence of deep uncertainties pertaining future climate change and how climate-sensitive systems respond to it. Given the many assumptions, one may legitimately ask 'Up to how many digits are the numbers produced by the model significant?' (Benessia et al., 2016). Another reason for caution is the plausible adverse impacts of quantification, for example blind trust in numbers. If decision-making authority is fully outsourced to number-based analysis, information on who wins and who loses could be gamed and abused (Aodha & Edmonds, 2017; Saltelli, 2020), and thus produces further injustices. Improving the institutions within which models are used has been proposed as an alternative solution for ethics of quantification (Saltelli, 2020). Similarly, in the context of planning for just adaptation and mitigation, climate justice should not be viewed only through numbers calculated by a set of tools. A more comprehensive account of justice in model-based climate planning could involve the incorporation of ethical imperatives from other views of justice—such as procedural justice in participatory modeling.

ACKNOWLEDGMENT

This work is funded by NWO Top Sector Water Call: Adaptation Pathways for socially inclusive development of urbanizing deltas (research number OND1362814).

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Bramka Arga Jafino: Conceptualization; investigation; methodology; writing-original draft; writing-review & editing. **Jan Kwakkel:** Conceptualization; investigation; methodology; writing-review & editing. **Behnam Taebi:** Investigation; writing-review & editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Bramka Arga Jafino  <https://orcid.org/0000-0001-6872-517X>

Jan H. Kwakkel  <https://orcid.org/0000-0001-9447-2954>

Behnam Taebi  <https://orcid.org/0000-0002-2244-2083>

ENDNOTE

¹ This paragraph is partially drawing on (Taebi, 2019, pp. 69–70).

RELATED WIREs ARTICLE

[Modeling impacts and adaptation in global IAMs](#)

[From environmental to climate justice: Climate change and the discourse of environmental justice](#)

[Sovereignty over natural resources and its implications for climate justice](#)

[Enfranchising the future: Climate justice and the representation of future generations](#)

REFERENCES

Ackerman, F., DeCanio, S. J., Howarth, R. B., & Sheeran, K. (2009). Limitations of integrated assessment models of climate change. *Climatic Change*, 95(3), 297–315. <https://doi.org/10.1007/s10584-009-9570-x>

- Adler, M., Anthoff, D., Bosetti, V., Garner, G., Keller, K., & Treich, N. (2017). Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, 7(6), 443–449. <https://doi.org/10.1038/nclimate3298>
- Adler, M. D. (2019). *Measuring social welfare: An introduction*. Oxford University Press.
- Adler, M. D., & Treich, N. (2015). Prioritarianism and climate change. *Environmental and Resource Economics*, 62(2), 279–308. <https://doi.org/10.1007/s10640-015-9960-7>
- Aerts, J. C. J. H., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., & Kunreuther, H. (2018). Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, 8(3), 193–199. <https://doi.org/10.1038/s41558-018-0085-1>
- Agusdinata, B. (2008). *Exploratory modeling and analysis: A promising method to deal with deep uncertainty*. Delft University of Technology.
- Ahmed, Y., Giasuddin Ahmed Choudhury, M., & Ahmed, S. (2017). Strategy formulation and adaptation pathways generation for sustainable development of western floodplain of Ganges. *Journal of Water Resource and Protection*, 9(06), 663–691. <https://doi.org/10.4236/jwarp.2017.96045>
- Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179–211. [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T)
- Akhtar, M. K., Wibe, J., Simonovic, S. P., & MacGee, J. (2013). Integrated assessment model of society-biosphere-climate-economy-energy system. *Environmental Modelling & Software*, 49, 1–21. <https://doi.org/10.1016/j.envsoft.2013.07.006>
- Andrée, B. P. J., Diogo, V., & Koomen, E. (2017). Efficiency of second-generation biofuel crop subsidy schemes: Spatial heterogeneity and policy design. *Renewable and Sustainable Energy Reviews*, 67, 848–862. <https://doi.org/10.1016/j.rser.2016.09.048>
- Anthoff, D., Hepburn, C., & Tol, R. S. J. (2009). Equity weighting and the marginal damage costs of climate change. *Ecological Economics*, 68(3), 836–849. <https://doi.org/10.1016/j.ecolecon.2008.06.017>
- Aodha, L. n., & Edmonds, B. (2017). Some pitfalls to beware when applying models to issues of policy relevance. In B. Edmonds & R. Meyer (Eds.), *Simulating social complexity: A handbook* (pp. 801–822). Springer International Publishing.
- Aronsson, T., Backlund, K., & Sahlén, L. (2010). Technology transfers and the clean development mechanism in a North–South general equilibrium model. *Resource and Energy Economics*, 32(3), 292–309. <https://doi.org/10.1016/j.reseneeco.2009.12.001>
- Arora-Jonsson, S. (2011). Virtue and vulnerability: Discourses on women, gender and climate change. *Global Environmental Change*, 21(2), 744–751. <https://doi.org/10.1016/j.gloenvcha.2011.01.005>
- Arrow, K., Cropper, M., Gollier, C., Groom, B., Heal, G., Newell, R., ... Portney, P. (2012). How should benefits and costs be discounted in an intergenerational context? The views of an expert panel. *Resources for the Future Discussion Paper*.
- Arrow, K. J., Cropper, M. L., Gollier, C., Groom, B., Heal, G. M., Newell, R. G., Nordhaus, W. D., Pindyck, R. S., Pizer, W. A., Portney, P. R., Sterner, T., Tol, R. S. J., & Weitzman, M. L. (2014). Should governments use a declining discount rate in project analysis? *Review of Environmental Economics and Policy*, 8(2), 145–163. <https://doi.org/10.1093/reep/reu008>
- Asheim, G. B. (2017). Sustainable growth. *Social Choice and Welfare*, 49(3), 825–848. <https://doi.org/10.1007/s00355-016-0977-9>
- Asheim, G. B., & Mitra, T. (2010). Sustainability and discounted utilitarianism in models of economic growth. *Mathematical Social Sciences*, 59(2), 148–169. <https://doi.org/10.1016/j.mathsocsci.2009.08.003>
- Atteridge, A., & Remling, E. (2018). Is adaptation reducing vulnerability or redistributing it? *WIREs Climate Change*, 9(1), e500. <https://doi.org/10.1002/wcc.500>
- Audsley, E., Pearn, K. R., Harrison, P. A., & Berry, P. M. (2008). The impact of future socio-economic and climate changes on agricultural land use and the wider environment in East Anglia and North West England using a metamodel system. *Climatic Change*, 90(1), 57–88. <https://doi.org/10.1007/s10584-008-9450-9>
- Balica, S. F., Wright, N. G., & van der Meulen, F. (2012). A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards*, 64(1), 73–105. <https://doi.org/10.1007/s11069-012-0234-1>
- Barbarà, S., & Jackson, M. (1988). Maximin, leximin, and the protective criterion: Characterizations and comparisons. *Journal of Economic Theory*, 46(1), 34–44.
- Baron, J. (1994). Nonconsequentialist decisions. *Behavioral and Brain Sciences*, 17(1), 1–10. <https://doi.org/10.1017/S0140525X0003301X>
- Barry, B. (1997). Sustainability and intergenerational justice. *Theoria*, 44(89), 43. <https://doi.org/10.3167/004058197783593443>
- Baum, S. D., & Easterling, W. E. (2010). Space-time discounting in climate change adaptation. *Mitigation and Adaptation Strategies for Global Change*, 15(6), 591–609. <https://doi.org/10.1007/s11027-010-9239-9>
- Beck, M., & Krueger, T. (2016). The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling. *WIREs Climate Change*, 7(5), 627–645. <https://doi.org/10.1002/wcc.415>
- Bednar, J., Jones-Rooy, A., & Page, S. E. (2015). Choosing a future based on the past: Institutions, behavior, and path dependence. *European Journal of Political Economy*, 40, 312–332. <https://doi.org/10.1016/j.ejpoleco.2015.09.004>
- Bell, D. (1993). *Communitarianism and its critics*. Clarendon Press.
- Bell, D. (2004). Environmental justice and Rawls' difference principle. *Environmental Ethics*, 26(3), 287–306.
- Benessia, A., Funtowicz, S., Giampietro, M., Pereira, Â. G., Ravetz, J. R., Saltelli, A., ... van der Sluijs, J. P. (2016). *Science on the verge*. Consortium for Science, Policy & Outcomes.
- Boadway, R. W., & Bruce, N. (1984). *Welfare economics*. Blackwell.
- Bosmans, K., & Öztürk, Z. E. (2018). An axiomatic approach to the measurement of envy. *Social Choice and Welfare*, 50(2), 247–264. <https://doi.org/10.1007/s00355-017-1082-4>

- Bossert, W., & Suzumura, K. (2017). The greatest unhappiness of the least number. *Social Choice and Welfare*, 49(3), 637–655. <https://doi.org/10.1007/s00355-017-1066-4>
- Botzen, W. J. W., & van den Bergh, J. C. J. M. (2014). Specifications of social welfare in economic studies of climate policy: Overview of criteria and related policy insights. *Environmental and Resource Economics*, 58(1), 1–33. <https://doi.org/10.1007/s10640-013-9738-8>
- Broome, J. (1992). *Counting the cost of global warming*. White Horse Press.
- Byskov, M. F., Hyams, K., Satyal, P., Anguelovski, I., Benjamin, L., Blackburn, S., Borie, M., Caney, S., Chu, E., Edwards, G., Fourie, K., Fraser, A., Heyward, C., Jeans, H., McQuistan, C., Paavola, J., Page, E., Pelling, M., Priest, S., ... Venn, A. (2019). An agenda for ethics and justice in adaptation to climate change. *Climate and Development*, 13, 1–9. <https://doi.org/10.1080/17565529.2019.1700774>
- Calvo, G. (1978). Some notes on time inconsistency and Rawls' maximin criterion. *The Review of Economic Studies*, 45(1), 97–102.
- Campos, A. S. (2018). Intergenerational justice today. *Philosophy Compass*, 13(3). e12477–n/a. <https://doi.org/10.1111/phc3.12477>
- Caney, S. (2005). Cosmopolitan justice, responsibility, and global climate change. *Leiden Journal of International Law*, 18, 747–775.
- Caney, S. (2009). Climate change and the future: Discounting for time, wealth, and risk. *Journal of Social Philosophy*, 40(2), 163–186.
- Chung, E.-S., & Lee, K. S. (2009). Prioritization of water management for sustainability using hydrologic simulation model and multicriteria decision making techniques. *Journal of Environmental Management*, 90(3), 1502–1511. <https://doi.org/10.1016/j.jenvman.2008.10.008>
- Ciullo, A., de Bruijn, K. M., Kwakkel, J. H., & Klijn, F. (2019). Accounting for the uncertain effects of hydraulic interactions in optimising embankments heights: Proof of principle for the IJssel River. *Journal of Flood Risk Management*, 12(S2), e12532. <https://doi.org/10.1111/jfr3.12532>
- Ciullo, A., Kwakkel, J. H., De Bruijn, K. M., Doorn, N., & Klijn, F. (2020). Efficient or fair? Operationalizing ethical principles in flood risk management: A case study on the Dutch-German Rhine. *Risk Analysis*, 40, 1844–1862. <https://doi.org/10.1111/risa.13527>
- Cohon, J. L., & Marks, D. H. (1975). A review and evaluation of multiobjective programming techniques. *Water Resources Research*, 11(2), 208–220.
- Conway, D., van Garderen, E. A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., Thurlow, J., Zhu, T., & Dalin, C. (2015). Climate and southern Africa's water–energy–food nexus. *Nature Climate Change*, 5, 837–846. <https://doi.org/10.1038/nclimate2735>
- Correljé, A., & Broekmans, B. (2015). Flood risk management in The Netherlands after the 1953 flood: A competition between the public value(s) of water. *Journal of Flood Risk Management*, 8(2), 99–115. <https://doi.org/10.1111/jfr3.12087>
- Cowell, F. A., & Flachaire, E. (2015). Chapter 6—Statistical methods for distributional analysis. In A. B. Atkinson & F. Bourguignon (Eds.), *Handbook of income distribution* (Vol. 2, pp. 359–465). Elsevier Science.
- D'Alessandro, S., Cieplinski, A., Distefano, T., & Dittmer, K. (2020). Feasible alternatives to green growth. *Nature Sustainability*, 3(4), 329–335. <https://doi.org/10.1038/s41893-020-0484-y>
- Davidson, M. D. (2015). Climate change and the ethics of discounting. *WIREs Climate Change*, 6(4), 401–412. <https://doi.org/10.1002/wcc.347>
- de Bruin, K. C., Dellink, R. B., & Tol, R. S. J. (2009). AD-DICE: An implementation of adaptation in the DICE model. *Climatic Change*, 95(1), 63–81. <https://doi.org/10.1007/s10584-008-9535-5>
- De Cian, E., Dasgupta, S., Hof, A. F., van Sluisveld, M. A. E., Köhler, J., Pfluger, B., & van Vuuren, D. P. (2018). Actors, decision-making, and institutions in quantitative system modelling. *Technological Forecasting and Social Change*, 151, 119480. <https://doi.org/10.1016/j.techfore.2018.10.004>
- de Ruig, L. T., Barnard, P. L., Botzen, W. J. W., Grifman, P., Hart, J. F., de Moel, H., Sadrpour, N., & Aerts, J. C. J. H. (2019). An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles. *Science of the Total Environment*, 678, 647–659. <https://doi.org/10.1016/j.scitotenv.2019.04.308>
- Deb, K., & Saxena, D. (2006). Searching for Pareto-optimal solutions through dimensionality reduction for certain large-dimensional multi-objective optimization problems. In *Proceedings of the World Congress on Computational Intelligence*. WCCI-2006.
- Demski, C., Butler, C., Parkhill, K. A., Spence, A., & Pidgeon, N. F. (2015). Public values for energy system change. *Global Environmental Change*, 34, 59–69. <https://doi.org/10.1016/j.gloenvcha.2015.06.014>
- Dennig, F. (2017). Climate change and the re-evaluation of cost-benefit analysis. *Climatic Change*, 151, 43–54. <https://doi.org/10.1007/s10584-017-2047-4>
- Dennig, F., Budolfson, M. B., Fleurbaey, M., Siebert, A., & Socolow, R. H. (2015). Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences of the United States of America*, 112(52), 15827–15832. <https://doi.org/10.1073/pnas.1513967112>
- Dhillon, A., & Mertens, J.-F. (1999). Relative Utilitarianism. *Econometrica*, 67(3), 471–498. <https://doi.org/10.1111/1468-0262.00033>
- Diaz, D., & Moore, F. (2017). Quantifying the economic risks of climate change. *Nature Climate Change*, 7(11), 774–782. <https://doi.org/10.1038/nclimate3411>
- Dietz, S., & Asheim, G. B. (2012). Climate policy under sustainable discounted utilitarianism. *Journal of Environmental Economics and Management*, 63(3), 321–335. <https://doi.org/10.1016/j.jeem.2012.01.003>
- Dittrich, R., Wreford, A., & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics*, 122, 79–89. <https://doi.org/10.1016/j.ecolecon.2015.12.006>
- Eijgenraam, C., Brekelmans, R., den Hertog, D., & Roos, K. (2016). Optimal strategies for flood prevention. *Management Science*, 63(5), 1644–1656. <https://doi.org/10.1287/mnsc.2015.2395>

- Fankhauser, S., Tol, R. S. J., & Pearce, D. W. (1997). The aggregation of climate change damages: A welfare theoretic approach. *Environmental and Resource Economics*, *10*(3), 249–266. <https://doi.org/10.1023/a:1026420425961>
- Fell, H., & Linn, J. (2013). Renewable electricity policies, heterogeneity, and cost effectiveness. *Journal of Environmental Economics and Management*, *66*(3), 688–707. <https://doi.org/10.1016/j.jeem.2013.03.004>
- Fleurbaey, M., Kartha, S., Bolwig, S., Chee, Y. L., Chen, Y., Corbera, E., ... Sagar, A. (2014). Sustainable development and equity. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, J. C. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, & T. Zwickel (Eds.), *Climate change 2014: Mitigation of climate change. Working group III contribution to the fifth assessment report of the intergovernmental panel on climate change* (pp. 238–350). Cambridge University Press.
- Fowlie, M., & Muller, N. (2013). *Market-based emissions regulation when damages vary across sources: What are the gains from differentiation?* National Bureau of Economic Research Working Paper Series, No. 18801. doi:<https://doi.org/10.3386/w18801>.
- Franssen, M. (2005). Arrow's theorem, multi-criteria decision problems and multi-attribute preferences in engineering design. *Research in Engineering Design*, *16*(1–2), 42–56. <https://doi.org/10.1007/s00163-004-0057-5>
- Füssel, H.-M. (2010a). How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment. *Global Environmental Change*, *20*(4), 597–611. <https://doi.org/10.1016/j.gloenvcha.2010.07.009>
- Füssel, H.-M. (2010b). Modeling impacts and adaptation in global IAMs. *WIREs Climate Change*, *1*(2), 288–303. <https://doi.org/10.1002/wcc.40>
- García-Muros, X., Burguillo, M., González-Eguino, M., & Romero-Jordán, D. (2017). Local air pollution and global climate change taxes: A distributional analysis for the case of Spain. *Journal of Environmental Planning and Management*, *60*(3), 419–436. <https://doi.org/10.1080/09640568.2016.1159951>
- Gardiner, S. M. (2010). Ethics and climate change: An introduction. *WIREs Climate Change*, *1*(1), 54–66. <https://doi.org/10.1002/wcc.16>
- Garner, G., Reed, P., & Keller, K. (2016). Climate risk management requires explicit representation of societal trade-offs. *Climatic Change*, *134*(4), 713–723. <https://doi.org/10.1007/s10584-016-1607-3>
- Gini, C. (1936). On the measure of concentration with special reference to income and statistics. *Colorado College Publication, General Series*, *208*(1), 73–79.
- Gohari, A., Mirchi, A., & Madani, K. (2017). System dynamics evaluation of climate change adaptation strategies for water resources Management in Central Iran. *Water Resources Management*, *31*(5), 1413–1434. <https://doi.org/10.1007/s11269-017-1575-z>
- Gold, D. F., Reed, P. M., Trindade, B. C., & Characklis, G. W. (2019). Identifying actionable compromises: Navigating Multi-City robustness conflicts to discover cooperative safe operating spaces for regional water supply portfolios. *Water Resources Research*, *55*(11), 9024–9050. <https://doi.org/10.1029/2019WR025462>
- Gosseries, A. (2008). On future generations' future rights. *Journal of Political Philosophy*, *16*(4), 446–474. <https://doi.org/10.1111/j.1467-9760.2008.00323.x>
- Gourevitch, J. D., Singh, N. K., Minot, J., Raub, K. B., Rizzo, D. M., Wemple, B. C., & Ricketts, T. H. (2020). Spatial targeting of floodplain restoration to equitably mitigate flood risk. *Global Environmental Change*, *61*, 102050. <https://doi.org/10.1016/j.gloenvcha.2020.102050>
- Grasso, M. (2007). A normative ethical framework in climate change. *Climatic Change*, *81*(3–4), 223–246. <https://doi.org/10.1007/s10584-006-9158-7>
- Grasso, M. (2010). The framework of justice. In M. Grasso (Ed.), *Justice in funding adaptation under the international climate change regime* (pp. 53–70). Springer.
- Green, D. (2016). The spatial distribution of extreme climate events, another climate inequity for the world's most vulnerable people. *Environmental Research Letters*, *11*(9), 091002.
- Grubb, M. (1995). Seeking fair weather: Ethics and the international debate on climate change. *International Affairs*, *71*(3), 463–496. <https://doi.org/10.2307/2624836>
- Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R., & Glavovic, B. (2020). Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, *20*(2), 37. <https://doi.org/10.1007/s10113-020-01623-8>
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. <https://doi.org/10.1016/j.gloenvcha.2012.12.006>
- Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E. v., & Deursen W. P. A. v. (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, *115*(3–4), 795–819. <https://doi.org/10.1007/s10584-012-0444-2>
- Haasnoot, M., van Aalst, M., Rozenberg, J., Dominique, K., Matthews, J., Bouwer, L. M., Kind, J., & Poff, N. L. (2019). Investments under non-stationarity: Economic evaluation of adaptation pathways. *Climatic Change*, *161*, 451–463. <https://doi.org/10.1007/s10584-019-02409-6>
- Hallegatte, S., & Rozenberg, J. (2017). Climate change through a poverty lens. *Nature Climate Change*, *7*, 250–256. <https://doi.org/10.1038/nclimate3253>
- Harrison, P. A., Dunford, R. W., Holman, I. P., & Rounsevell, M. D. A. (2016). Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change*, *6*, 885–890. <https://doi.org/10.1038/nclimate3039>
- Heal, G. (1997). Discounting and climate change; an editorial comment. *Climatic Change*, *37*(2), 335–343. <https://doi.org/10.1023/a:1005384629724>
- Heal, G., & Millner, A. (2013). *Discounting under disagreement*. National Bureau of Economic Research Retrieved from <http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2013/04/w18999.pdf>

- Heilmann, C. (2017). Values in time discounting. *Science and Engineering Ethics*, 23(5), 1333–1349. <https://doi.org/10.1007/s11948-017-9950-y>
- Herman, J., Reed, P., Zeff, H., & Characklis, G. (2015). How should robustness be defined for water systems planning under change? *Journal of Water Resources Planning and Management*, 141(10), 04015012. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000509](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000509)
- Heyward, M. (2007). Equity and international climate change negotiations: A matter of perspective. *Climate Policy*, 7(6), 518–534. <https://doi.org/10.1080/14693062.2007.9685674>
- Hidayatno, A., Dinianyadharani, A. K., & Sutrisno, A. (2017). Scenario analysis of the Jakarta coastal Defence strategy: Sustainable indicators impact assessment. *International Journal of Innovation and Sustainable Development*, 11(1), 37–52. <https://doi.org/10.1504/ijisd.2017.080626>
- Höhne, N., den Elzen, M., & Escalante, D. (2014). Regional GHG reduction targets based on effort sharing: A comparison of studies. *Climate Policy*, 14(1), 122–147. <https://doi.org/10.1080/14693062.2014.849452>
- Hope, C. (2008). Discount rates, equity weights and the social cost of carbon. *Energy Economics*, 30(3), 1011–1019. <https://doi.org/10.1016/j.eneco.2006.11.006>
- Hsu, W.-K., Huang, P.-C., Chang, C.-C., Chen, C.-W., Hung, D.-M., & Chiang, W.-L. (2011). An integrated flood risk assessment model for property insurance industry in Taiwan. *Natural Hazards*, 58(3), 1295–1309. <https://doi.org/10.1007/s11069-011-9732-9>
- Huang, H., Roland-Holst, D., Springer, C., Lin, J., Cai, W., & Wang, C. (2019). Emissions trading systems and social equity: A CGE assessment for China. *Applied Energy*, 235, 1254–1265. <https://doi.org/10.1016/j.apenergy.2018.11.056>
- Hulme, M. (2009). *Why we disagree about climate change: Understanding controversy, inaction and opportunity*. Cambridge University Press.
- Ikeme, J. (2003). Equity, environmental justice and sustainability: Incomplete approaches in climate change politics. *Global Environmental Change*, 13(3), 195–206. [https://doi.org/10.1016/S0959-3780\(03\)00047-5](https://doi.org/10.1016/S0959-3780(03)00047-5)
- Jafino, B. A., Haasnoot, M., & Kwakkel, J. H. (2019). What are the merits of endogenising land-use change dynamics into model-based climate adaptation planning? *Socio-Environmental Systems Modeling*, 1, 16126–16126. <https://doi.org/10.18174/sesmo.2019a16126>
- Karnein, A. (2015). Climate change and justice between nonoverlapping generations. *Global Justice: Theory Practice Rhetoric*, 8(2), 43–65.
- Kartha, S., Athanasiou, T., Caney, S., Cripps, E., Dooley, K., Dubash, N. K., Fei, T., Harris, P. G., Holz, C., Lahn, B., Moellendorf, D., Müller, B., Roberts, J. T., Sagar, A., Shue, H., Singer, P., & Winkler, H. (2018). Cascading biases against poorer countries. *Nature Climate Change*, 8(5), 348–349. <https://doi.org/10.1038/s41558-018-0152-7>
- Kasprzyk, J. R., Nataraj, S., Reed, P. M., & Lempert, R. J. (2013). Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software*, 42, 55–71. <https://doi.org/10.1016/j.envsoft.2012.12.007>
- Kasprzyk, J. R., Reed, P. M., & Hadka, D. M. (2016). Battling arrow's paradox to discover robust water management alternatives. *Journal of Water Resources Planning and Management*, 142(2), 04015053. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000572](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000572)
- Kelly, R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., ... Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software*, 47, 159–181. <https://doi.org/10.1016/j.envsoft.2013.05.005>
- Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., Fragkos, P., Guivarch, C., Harmsen, M., Lefèvre, J., le Gallic, T., Leimbach, M., McDowall, W., Mercure, J. F., Schaeffer, R., Trutnevte, E., & Wagner, F. (2021). Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models. *Environmental Research Letters*, 16, 053006–053006.
- Kermisch, C., & Taebi, B. (2017). Sustainability, ethics and nuclear energy: Escaping the dichotomy. *Sustainability*, 9(3), 446–459. <https://doi.org/10.3390/su9030446>
- Kind, J., Wouter Botzen, W. J., & Aerts, J. C. J. H. (2017). Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management. *WIREs Climate Change*, 8(2), e446–e446. <https://doi.org/10.1002/wcc.446>
- Klinsky, S., Roberts, T., Huq, S., Okereke, C., Newell, P., Dauvergne, P., O'Brien, K., Schroeder, H., Tschakert, P., Clapp, J., Keck, M., Biermann, F., Liverman, D., Gupta, J., Rahman, A., Messner, D., Pellow, D., & Bauer, S. (2017). Why equity is fundamental in climate change policy research. *Global Environmental Change*, 44, 170–173. <https://doi.org/10.1016/j.gloenvcha.2016.08.002>
- Koks, E. E., Jongman, B., Husby, T. G., & Botzen, W. J. W. (2015). Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environmental Science & Policy*, 47, 42–52. <https://doi.org/10.1016/j.envsci.2014.10.013>
- Kolm, S.-C. (1977). Multidimensional egalitarianisms. *The Quarterly Journal of Economics*, 91(1), 1–13.
- Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Cariño-Olvera, M., Fullerton, D., ... Jotzo, F. (2014). Social, economic and ethical concepts and methods. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. B. P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwicker, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 173–248). Cambridge University Press.
- Konow, J. (2001). Fair and square: The four sides of distributive justice. *Journal of Economic Behavior & Organization*, 46(2), 137–164. [https://doi.org/10.1016/S0167-2681\(01\)00194-9](https://doi.org/10.1016/S0167-2681(01)00194-9)
- Konow, J. (2003). Which is the fairest one of all? A positive analysis of justice theories. *Journal of Economic Literature*, 41(4), 1188–1239.
- Krey, V. (2014). Global energy-climate scenarios and models: A review. *WIREs Energy and Environment*, 3(4), 363–383. <https://doi.org/10.1002/wene.98>
- Kwakkel, J. H. (2017). The exploratory modeling workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, 96, 239–250. <https://doi.org/10.1016/j.envsoft.2017.06.054>

- Kymlicka, W. (2002). *Contemporary political philosophy: An introduction*. Oxford University Press.
- Lau, J. D., Gurney, G. G., & Cinner, J. (2021). Environmental justice in coastal systems: Perspectives from communities confronting change. *Global Environmental Change*, 66, 102208. <https://doi.org/10.1016/j.gloenvcha.2020.102208>
- Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. Rand Corporation.
- Li, S., Juhász-Horváth, L., Pintér, L., Rounsevell, M. D. A., & Harrison, P. A. (2018). Modelling regional cropping patterns under scenarios of climate and socio-economic change in Hungary. *Science of the Total Environment*, 622–623, 1611–1620. <https://doi.org/10.1016/j.scitotenv.2017.10.038>
- List, C. (2012). The theory of judgment aggregation: An introductory review. *Synthese*, 187(1), 179–207.
- Little, J. C., Hester, E. T., Elsworth, S., Filz, G. M., Sandu, A., Carey, C. C., Iwanaga, T., & Jakeman, A. J. (2019). A tiered, system-of-systems modeling framework for resolving complex socio-environmental policy issues. *Environmental Modelling & Software*, 112, 82–94. <https://doi.org/10.1016/j.envsoft.2018.11.011>
- Luis, A. B.-T., Marco, J., Hallie, E., Andres, B., Fidel, S.-C., Paola, G.-P., & Yosune, M. (2019). Spatially-explicit simulation of two-way coupling of complex socio-environmental systems: Socio-hydrological risk and decision making in Mexico City. *Socio-Environmental Systems Modelling*, 1(0), 16129–16129. <https://doi.org/10.18174/sesmo.2019a16129>
- Machado, E. A., & Ratick, S. (2018). Implications of indicator aggregation methods for global change vulnerability reduction efforts. *Mitigation and Adaptation Strategies for Global Change*, 23(7), 1109–1141. <https://doi.org/10.1007/s11027-017-9775-7>
- Manne, A. S., & Richels, R. G. (2005). Merge: An integrated assessment model for global climate change. In R. Loulou, J.-P. Waub, & G. Zaccour (Eds.), *Energy and environment* (pp. 175–189). Springer US.
- Mathias, J.-D., Debeljak, M., Deffuant, G., Diemer, A., Dierickx, F., Donges, J. F., Gladkykh, G., Heitzig, J., Holtz, G., Obergassel, W., Pellaud, F., Sánchez, A., Trajanov, A., & Videira, N. (2020). Grounding social foundations for integrated assessment models of climate change. *Earth's Future*, 8(7), e2020EF001573. <https://doi.org/10.1029/2020EF001573>
- Meinard, Y., & Tsoukiás, A. (2019). On the rationality of decision aiding processes. *European Journal of Operational Research*, 273(3), 1074–1084. <https://doi.org/10.1016/j.ejor.2018.09.009>
- Mérel, P., & Wimberger, E. (2012). Improving air quality in California's San Joaquin Valley: The role of vehicle heterogeneity in optimal emissions abatement. *Journal of Environmental Economics and Management*, 63(2), 169–186. <https://doi.org/10.1016/j.jeem.2011.10.004>
- Michas, S., Stavrakas, V., Papadelis, S., & Flamos, A. (2020). A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways. *Energy Policy*, 139, 111350. <https://doi.org/10.1016/j.enpol.2020.111350>
- Millner, A. (2013). On welfare frameworks and catastrophic climate risks. *Journal of Environmental Economics and Management*, 65(2), 310–325. <https://doi.org/10.1016/j.jeem.2012.09.006>
- Moallemi, E. A., Zare, F., Reed, P. M., Elsworth, S., Ryan, M. J., & Bryan, B. A. (2020). Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems. *Environmental Modelling & Software*, 123, 104551. <https://doi.org/10.1016/j.envsoft.2019.104551>
- Münier, B., Birr-Pedersen, K., & Schou, J. S. (2004). Combined ecological and economic modelling in agricultural land use scenarios. *Ecological Modelling*, 174(1), 5–18. <https://doi.org/10.1016/j.ecolmodel.2003.12.040>
- Negishi, T. (1972). *General equilibrium theory and international trade*. North-Holland Publishing Company.
- Nguyen, T. T., & Rothe, J. (2014). Minimizing envy and maximizing average Nash social welfare in the allocation of indivisible goods. *Discrete Applied Mathematics*, 179, 54–68. <https://doi.org/10.1016/j.dam.2014.09.010>
- Nordhaus, W. (2014). Estimates of the social cost of carbon: Concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1(1/2), 273–312. <https://doi.org/10.1086/676035>
- Nordhaus, W. D. (2011). *Estimates of the social cost of carbon: Background and results from the RICE-2011 model*. National Bureau of Economic Research Retrieved from <https://www.nber.org/papers/w17540>
- Nordhaus, W. D., & Boyer, J. (2000). *Warming the world: Economic models of global warming*. MIT Press.
- Nordhaus, W. D., & Yang, Z. (1996). A regional dynamic general-equilibrium model of alternative climate-change strategies. *The American Economic Review*, 86(4), 741–765.
- Okereke, C. (2010). Climate justice and the international regime. *WIREs Climate Change*, 1(3), 462–474. <https://doi.org/10.1002/wcc.52>
- Oshima, H. T. (1970). Income inequality and economic growth postwar experience of Asian countries. *Malayan Economic Review*, 15(2), 7–41.
- Paavola, J., & Adger, W. N. (2006). Fair adaptation to climate change. *Ecological Economics*, 56(4), 594–609. <https://doi.org/10.1016/j.ecolecon.2005.03.015>
- Padilla, E. (2002). Intergenerational equity and sustainability. *Ecological Economics*, 41(1), 69–83.
- Page, E. (1999). Intergenerational justice and climate change. *Political Studies*, 47(1), 53–66. <https://doi.org/10.1111/1467-9248.00187>
- Page, E. A. (2007). *Climate change, justice and future generations*. Edward Elgar Publishing.
- Page, E. A., & Heyward, C. (2016). Compensating for climate change loss and damage. *Political Studies*, 65(2), 356–372. <https://doi.org/10.1177/0032321716647401>
- Palutikof, J. P., Street, R. B., & Gardiner, E. P. (2019). Decision support platforms for climate change adaptation: An overview and introduction. *Climatic Change*, 153(4), 459–476. <https://doi.org/10.1007/s10584-019-02445-2>
- Parfit, D. (2012). Another defence of the priority view. *Utilitas*, 24(3), 399–440.

- Patt, A. G., van Vuuren, D. P., Berkhout, F., Aaheim, A., Hof, A. F., Isaac, M., & Mechler, R. (2010). Adaptation in integrated assessment modeling: Where do we stand? *Climatic Change*, *99*(3), 383–402. <https://doi.org/10.1007/s10584-009-9687-y>
- Pazner, E. A., & Schmeidler, D. (1978). Egalitarian equivalent allocations: A new concept of economic equity. *The Quarterly Journal of Economics*, *92*(4), 671–687. <https://doi.org/10.2307/1883182>
- Pelling, M., & Garschagen, M. (2019). Put equity first in climate adaptation. *Nature*, *569*, 327–329.
- Pesch, U., Correljé, A., Cuppen, E., & Taebi, B. (2017). Energy justice and controversies: Formal and informal assessment in energy projects. *Energy Policy*, *109*, 825–834. <https://doi.org/10.1016/j.enpol.2017.06.040>
- Peters, G. P., Andrew, R. M., Solomon, S., & Friedlingstein, P. (2015). Measuring a fair and ambitious climate agreement using cumulative emissions. *Environmental Research Letters*, *10*(10), 105004. <https://doi.org/10.1088/1748-9326/10/10/105004>
- Pezzey, J. C. V. (2019). Why the social cost of carbon will always be disputed. *WIREs Climate Change*, *10*(1), e558. <https://doi.org/10.1002/wcc.558>
- Pindyck, R. S. (2017). The use and misuse of models for climate policy. *Review of Environmental Economics and Policy*, *11*(1), 100–114.
- Popp, D. (2004). ENTICE: Endogenous technological change in the DICE model of global warming. *Journal of Environmental Economics and Management*, *48*(1), 742–768. <https://doi.org/10.1016/j.jeem.2003.09.002>
- Posner, E. A., & Weisbach, D. (2010). *Climate change justice*. Princeton University Press.
- Posner, R. A. (1979). Utilitarianism, economics, and legal theory. *The Journal of Legal Studies*, *8*(1), 103–140.
- Radhakrishnan, M., Nguyen, H. Q., Gersonius, B., Pathirana, A., Vinh, K. Q., Ashley, R. M., & Zevenbergen, C. (2017). Coping capacities for improving adaptation pathways for flood protection in Can Tho, Vietnam. *Climatic Change*, *149*, 29–41. <https://doi.org/10.1007/s10584-017-1999-8>
- Rao, N. D. (2013). Distributional impacts of climate change mitigation in Indian electricity: The influence of governance. *Energy Policy*, *61*, 1344–1356. <https://doi.org/10.1016/j.enpol.2013.05.103>
- Rao, N. D., van Ruijven, B. J., Riahi, K., & Bosetti, V. (2017). Improving poverty and inequality modelling in climate research. *Nature Climate Change*, *7*(12), 857–862.
- Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., ... Le Quéré, C. (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, *4*(10), 873–879. <https://doi.org/10.1038/nclimate2384>
- Rawls, J. (1974). Some reasons for the maximin criterion. *The American Economic Review*, *64*(2), 141–146.
- Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), 38–43. <https://doi.org/10.1038/nclimate3186>
- Rosenhead, J. (1980). Planning under uncertainty: II. A methodology for robustness analysis. *Journal of the Operational Research Society*, *31*(4), 331–341. <https://doi.org/10.1057/jors.1980.60>
- Rosenhead, J., Elton, M., & Gupta, S. K. (1972). Robustness and optimality as criteria for strategic decisions. *Journal of the Operational Research Society*, *23*(4), 413–431. <https://doi.org/10.1057/jors.1972.72>
- Sáez, C. A., & Requena, J. C. (2007). Reconciling sustainability and discounting in cost–benefit analysis: A methodological proposal. *Ecological Economics*, *60*(4), 712–725. <https://doi.org/10.1016/j.ecolecon.2006.05.002>
- Saltelli, A. (2020). Ethics of quantification or quantification of ethics? *Futures*, *116*, 102509. <https://doi.org/10.1016/j.futures.2019.102509>
- Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., ... Mayo, D. (2020). Five ways to ensure that models serve society: A manifesto. *Nature*, *582*, 482–484.
- Sarofim, M. C., & Reilly, J. M. (2011). Applications of integrated assessment modeling to climate change. *WIREs Climate Change*, *2*(1), 27–44. <https://doi.org/10.1002/wcc.93>
- Savini, F., Majoor, S., & Salet, W. (2015). Dilemmas of planning: Intervention, regulation, and investment. *Planning Theory*, *14*(3), 296–315. <https://doi.org/10.1177/1473095214531430>
- Sayers, P., Penning-Rowsell, E. C., & Horritt, M. (2018). Flood vulnerability, risk, and social disadvantage: Current and future patterns in the UK. *Regional Environmental Change*, *18*(2), 339–352. <https://doi.org/10.1007/s10113-017-1252-z>
- Schill, C., Anderies, J. M., Lindahl, T., Folke, C., Polasky, S., Cárdenas, J. C., Crépin, A. S., Janssen, M. A., Norberg, J., & Schlüter, M. (2019). A more dynamic understanding of human behaviour for the Anthropocene. *Nature Sustainability*, *2*(12), 1075–1082. <https://doi.org/10.1038/s41893-019-0419-7>
- Schinko, T., Mechler, R., & Hochrainer-Stigler, S. (2019). The risk and policy space for loss and damage: Integrating notions of distributive and compensatory justice with comprehensive climate risk management. In R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, & J. Linnerooth-Bayer (Eds.), *Loss and damage from climate change: Concepts, methods and policy options* (pp. 83–110). Springer International Publishing.
- Schlosberg, D. (2009). *Defining environmental justice: Theories, movements, and nature*. Oxford University Press.
- Schneider, S., & Lane, J. (2005). Integrated assessment modeling of global climate change: Much has been learned—Still a long and bumpy road ahead. *Integrated Assessment*, *5*(1), 41–75.
- Schneider, S. H. (1997). Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions? *Environmental Modeling & Assessment*, *2*(4), 229–249. <https://doi.org/10.1023/a:1019090117643>
- Sen, A. (1997). *On economic inequality*. Oxford university press.
- Sen, A. (2018). *Collective choice and social welfare*. Harvard University Press.
- Shields, L. (2012). The prospects for Sufficiencyarianism. *Utilitas*, *24*(1), 101–117. <https://doi.org/10.1017/S0953820811000392>

- Sikdar, S. K. (2009). On aggregating multiple indicators into a single metric for sustainability. *Clean Technologies and Environmental Policy*, 11(2), 157–161. <https://doi.org/10.1007/s10098-009-0225-4>
- Singer, P. (2002). *One world: The ethics of globalization*. Yale University Press.
- Smajgl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D., & Vu, P. T. (2015). Responding to rising sea levels in the Mekong Delta. *Nature Climate Change*, 5(2), 167–174. <https://doi.org/10.1038/nclimate2469>
- Sondoss, E., Tatiana, F., Anthony, J. J., Albert, J. K., Moira, L. Z., Ioannis, N. A., ... Steve, J. L. (2020). Eight grand challenges in socio-environmental systems modeling. *Socio-Environmental Systems Modelling*, 2(0), 16226–16226. <https://doi.org/10.18174/sesmo.2020a16226>
- Sprumont, Y. (2013). On relative egalitarianism. *Social Choice and Welfare*, 40(4), 1015–1032. <https://doi.org/10.1007/s00355-012-0653-7>
- Stanton, E. A. (2011). Negishi welfare weights in integrated assessment models: The mathematics of global inequality. *Climatic Change*, 107(3), 417–432. <https://doi.org/10.1007/s10584-010-9967-6>
- Stanton, E. A., Ackerman, F., & Kartha, S. (2009). Inside the integrated assessment models: Four issues in climate economics. *Climate and Development*, 1(2), 166–184. <https://doi.org/10.3763/cdev.2009.0015>
- Stehfest, E., van Vuuren, D., Bouwman, L., & Kram, T. (2014). *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. Netherlands Environmental Assessment Agency (PBL).
- Stiglitz, J. E. (2019). Addressing climate change through price and non-price interventions. *European Economic Review*, 119, 594–612. <https://doi.org/10.1016/j.eurocorev.2019.05.007>
- Storm, S. (2017). How the invisible hand is supposed to adjust the natural thermostat: A guide for the perplexed. *Science and Engineering Ethics*, 23(5), 1307–1331. <https://doi.org/10.1007/s11948-016-9780-3>
- Suzumura, K. (2001). Introduction. In K. Arrow, A. Sen, & K. Suzumura (Eds.), *Handbook of social choice and welfare*. Elsevier.
- Taconet, N., Méjean, A., & Guivarch, C. (2020). Influence of climate change impacts and mitigation costs on inequality between countries. *Climatic Change*, 160(1), 15–34. <https://doi.org/10.1007/s10584-019-02637-w>
- Taebi, B. (2019). Justice and good governance in nuclear disasters. In D. P. O'Mathúna & I. de Miguel Beriain (Eds.), *Ethics and law for chemical, biological, radiological, nuclear & explosive crises* (pp. 65–74). Springer International Publishing.
- Taebi, B., Kwakkel, J. H., & Kermisch, C. (2020). Governing climate risks in the face of normative uncertainties. *WIREs Climate Change*, e666. <https://doi.org/10.1002/wcc.666>
- Thaler, T., & Hartmann, T. (2016). Justice and flood risk management: Reflecting on different approaches to distribute and allocate flood risk management in Europe. *Natural Hazards*, 83(1), 129–147. <https://doi.org/10.1007/s11069-016-2305-1>
- Thomas, K., Hardy, R. D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J. T., Rockman, M., Warner, B. P., & Winthrop, R. (2019). Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, 10(2), e565. <https://doi.org/10.1002/wcc.565>
- Thomas, K. A., & Warner, B. P. (2019). Weaponizing vulnerability to climate change. *Global Environmental Change*, 57, 101928. <https://doi.org/10.1016/j.gloenvcha.2019.101928>
- Thornton, P. K., Jones, P. G., Alagarswamy, G., Andresen, J., & Herrero, M. (2010). Adapting to climate change: Agricultural system and household impacts in East Africa. *Agricultural Systems*, 103(2), 73–82. <https://doi.org/10.1016/j.agsy.2009.09.003>
- Tol, R. S. J. (2001). Equitable cost-benefit analysis of climate change policies. *Ecological Economics*, 36(1), 71–85. [https://doi.org/10.1016/S0921-8009\(00\)00204-4](https://doi.org/10.1016/S0921-8009(00)00204-4)
- Tol, R. S. J., Downing, T. E., Kuik, O. J., & Smith, J. B. (2004). Distributional aspects of climate change impacts. *Global Environmental Change*, 14(3), 259–272. <https://doi.org/10.1016/j.gloenvcha.2004.04.007>
- Törnblom, K. Y., & Vermunt, R. (1999). An integrative perspective on social justice: Distributive and procedural fairness evaluations of positive and negative outcome allocations. *Social Justice Research*, 12(1), 39–64. <https://doi.org/10.1023/A:1023226307252>
- Triet, N. V. K., Dung, N. V., Merz, B., & Apel, H. (2018). Towards risk-based flood management in highly productive paddy rice cultivation—Concept development and application to the Mekong Delta. *Natural Hazards and Earth System Sciences*, 18(11), 2859–2876. <https://doi.org/10.5194/nhess-18-2859-2018>
- Trindade, B. C., Reed, P. M., Herman, J. D., Zeff, H. B., & Characklis, G. W. (2017). Reducing regional drought vulnerabilities and multi-city robustness conflicts using many-objective optimization under deep uncertainty. *Advances in Water Resources*, 104, 195–209. <https://doi.org/10.1016/j.advwatres.2017.03.023>
- van de Poel, I. (2018). Design for value change. *Ethics and Information Technology*, 20, 1–5. <https://doi.org/10.1007/s10676-018-9461-9>
- Van Hootegeem, A., Abts, K., & Meuleman, B. (2020). Differentiated distributive justice preferences? Configurations of preferences for equality, equity and need in three welfare domains. *Social Justice Research*, 33(3), 257–283. <https://doi.org/10.1007/s11211-020-00354-9>
- Van Ruijven, B. J., O'Neill, B. C., & Chateau, J. (2015). Methods for including income distribution in global CGE models for long-term climate change research. *Energy Economics*, 51, 530–543. <https://doi.org/10.1016/j.eneco.2015.08.017>
- Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. V. D., Seitzinger, S., Steffen, W., & Syvitski, J. (2016). Methods and approaches to modelling the Anthropocene. *Global Environmental Change*, 39, 328–340. <https://doi.org/10.1016/j.gloenvcha.2015.08.007>
- Vermunt, R., & Törnblom, K. (1996). Introduction: Distributive and procedural justice. *Social Justice Research*, 9(4), 305–310. <https://doi.org/10.1007/BF02196987>
- Vezér, M., Bakker, A., Keller, K., & Tuana, N. (2018). Epistemic and ethical trade-offs in decision analytical modelling. *Climatic Change*, 147(1), 1–10. <https://doi.org/10.1007/s10584-017-2123-9>

- Voinov, A., & Shugart, H. H. (2013). 'Integronsters', integral and integrated modeling. *Environmental Modelling & Software*, 39, 149–158. <https://doi.org/10.1016/j.envsoft.2012.05.014>
- Walsh, B., Ciais, P., Janssens, I. A., Peñuelas, J., Riahi, K., Rydzak, F., van Vuuren, D. P., & Obersteiner, M. (2017). Pathways for balancing CO₂ emissions and sinks. *Nature Communications*, 8(1), 14856. <https://doi.org/10.1038/ncomms14856>
- Watkiss, P. (2011). Aggregate economic measures of climate change damages: Explaining the differences and implications. *WIREs Climate Change*, 2(3), 356–372. <https://doi.org/10.1002/wcc.111>
- Wild, T. B., Reed, P. M., Loucks, D. P., Mallen-Cooper, M., & Jensen, E. D. (2019). Balancing hydropower development and ecological impacts in the Mekong: Tradeoffs for Sambor mega dam. *Journal of Water Resources Planning and Management*, 145(2), 05018019. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0001036](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001036)
- Wood, B., Stringer, L., Dougill, A., & Quinn, C. (2018). Socially just triple-wins? A framework for evaluating the social justice implications of climate compatible development. *Sustainability*, 10(1), 211–231. <https://doi.org/10.3390/su10010211>
- Yang, Z., & Nordhaus, W. D. (2006). Magnitude and direction of technological transfers for mitigating GHG emissions. *Energy Economics*, 28(5), 730–741. <https://doi.org/10.1016/j.eneco.2006.05.015>
- Zuber, S., & Asheim, G. B. (2012). Justifying social discounting: The rank-discounted utilitarian approach. *Journal of Economic Theory*, 147(4), 1572–1601.

How to cite this article: Jafino, B. A., Kwakkel, J. H., & Taebi, B. (2021). Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *Wiley Interdisciplinary Reviews: Climate Change*, e721. <https://doi.org/10.1002/wcc.721>