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Does Distributive Justice Improve Welfare Outcomes in Climate Adaptation? An Exploration Using an Agent-Based Model of a Stylized Social–Environmental System

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Abstract: Scholars increasingly propose distributive justice as a means to foster effective and fair outcomes in climate adaptation. To advance the discussion on its place in climate policy, it is desirable to be able to quantitatively assess the effects of different principles of distribution on the well-being of unequally vulnerable individuals and groups. Here, we present an agent-based model of a stylized social–environmental system subject to an external stress such as a climate change impact, in which individuals with unequal access to resources attempt to fulfil an essential need through resource consumption. This causes environmental damage, and a balance must be found between the processes of resource consumption and environmental degradation to achieve well-being for people and stability for the environment. We operationalize different principles for redistributing resource access as interaction rules in the model and compare their tendency to allow such a balance to emerge. Our results indicate that while outcome patterns and effectiveness may vary among principles, redistribution generally improves well-being and system stability. We discuss some implications of our findings as they pertain to addressing the climate crisis and end by outlining the next steps for the research.

Keywords: climate adaptation; distributive justice; social systems modelling; resource consumption; environmental impact; agent-based modelling; principles of distribution; egalitarianism; sufficientarianism; capability approach

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1. Introduction

The intensifying crises of climate and ecological breakdown have as their root cause increasing societal throughput of the Earth's natural resources [1]. The bulk of this throughput is driven by high levels of consumption by a minority of the global population, with the attendant polluting emissions increasingly degrading the state of the global environmental commons [2,3]. Communities that have contributed little to these crises tend to bear the brunt of their impacts [4], and at the same time they often lack the resources needed to cope with them [5,6]. Such inequities arise out of unequal socio-political, environmental, and personal circumstances, which render people and groups unequally able to access resources and exposed to risks [7,8]. These differences manifest both across and within societies, and for a climate adaptation context, they engender unequal vulnerability to climate change impacts and unequal ability to undertake adaptive actions [9,10].

Unequal and unjust distributions of vulnerability and the resources required to overcome them are recognized as fundamental barriers to effective climate adaptation at individual and societal levels [5,11]. Social structures and institutions can either enhance security or exacerbate vulnerability by shaping the distribution of resources in society. Distributive justice is an ethical theory that provides guidance on the societal distributions of risks and benefits that are morally acceptable, and, therefore, whether it is right to stay with current policies or to modify them [12]. The impetus for addressing distributive injustices in climate adaptation arises when we consider the question of how to protect our own human rights from behind the 'veil of ignorance' [13]. Scholars also advocate for a rebalancing of benefits and risks as a matter of upholding the principles of equity and solidarity laid out in the UNFCCC [14]. Various conceptions of distributive principles exist—e.g., egalitarianism, utilitarianism, sufficientarianism, desert-based principles, etc.—and they may not all help engender equitable welfare outcome patterns. The goal of this work is to contribute quantitative insight into the relative potential of certain distributive principles to foster equitable welfare outcomes in climate adaptation contexts. In doing so, we add a fresh perspective to the discussion on the place of distributive justice in climate policy.

To that end, we present an agent-based model where we formalize different principles of distribution in a stylized finite resource social–environmental system. This enables us to perform a comparative assessment of their effects on the well-being of unequally vulnerable people and groups. We study the patterns of outcomes that different distributive principles yield in order to identify those that may be able to achieve fairer outcomes and more stable environmental systems than a baseline scenario without redistribution.

The structure of the rest of this article is as follows: Section 2 gives an overview of the concepts that form the theoretical background for this work; Section 3 introduces the agent-based model; Section 4 presents the experimental setup and results; and Section 5 discusses the contributions of this work and the implications of its findings, along with its limitations and potential future work.

2. Theoretical background

2.1. Vulnerability

Vulnerability may be considered as the state of individuals, groups, or communities that determines their ability to cope with and adapt to any external stress placed on their livelihoods and well-being [6]. The IPCC's risk framework identifies vulnerability as one of the determinants of risk in climate adaptation along with exposure to hazards. The vulnerability of individuals and groups in a community is related to their adaptive capacity to deal with hazardous conditions [11]. A key societal observation is that people are not equally vulnerable to climate change impacts, nor do they possess the same capacity and resources for adaptation. Vulnerability and adaptive capacity are determined by the availability of resources and the entitlement and ability of individuals and groups to make use of these resources [6]. A host of personal, social, political, and environmental factors influence this entitlement and ability. For example, both income (immediately accessible resources) and wealth (disposable capital assets) are important for agricultural communities to be able to cope with the impacts of drought [15]. Other studies point to a broad variety of assets, such as economic capital, physical capital, natural capital, human capital, etc., as being crucial [8,16]. In addition, scholars also recognize social relations and social capital as playing a key role in determining adaptive capacity [10,17].

2.2. Role of Distributive Justice

Indeed, societal structures and institutions can either enhance security or exacerbate vulnerability by shaping the distribution of resources in society. The frameworks with which society decides upon its structures, laws, and institutions are important because the distributions of (access to) resources that result from them impact peoples' lives [12]. Distributive justice is concerned with the shape or manner in which resources (and outcomes) are distributed across people, and which frameworks and resulting distributions are morally acceptable. Distributive justice theory seeks to provide moral guidance for laws and policies that affect the distribution of benefits and costs, and, therefore, the opportunity to achieve well-being among people in society.

Distributive justice is a crucial concern in climate adaptation because people with differential adaptive capacities and contribution to climate change are often unequally exposed to its impacts. Moreover, adaptation actions and policies are likely to affect different individuals and groups unevenly and give rise to unjust distributions of costs and benefits, sometimes even exacerbating existing injustices [18]. The goal of distributive justice theory is to provide an ethical standard to help ensure that risks and benefits are distributed across societal members in a just manner. The three central considerations in distributive justice relate to the shape, unit, and scope of distribution [19]. (The discussion of the unit of distribution, or what is being distributed, is taken up in the next sub-section.) Different principles of distribution can be followed, which may lead to different shapes or patterns of distribution. An egalitarian principle, for instance, would prescribe that every person should have an equal amount of material goods and resources, whereas a Rawlsian difference principle would tolerate inequality among individuals as long as the new distribution benefits the least well-off. A utilitarian principle would prioritise aggregate welfare maximization [12]. The different patterns of distributive outcomes obtained from varying principles are each likely to favour the well-being of some people and groups more than others. A vital question is, to what extent are different principles of distribution likely to meet standards of both justice and effectiveness? An approach to evaluate and compare distribution patterns arising from different justice conceptions or principles may help guide policymakers towards climate adaptation action where benefits and burdens are shared equitably in society.

2.3. The Capability Approach to Operationalize Distributive Justice

Just as there are different principles that may form the basis for distributing (access to) resources, there are different entities that matter for peoples' well-being and whose units we may want to distribute. The capability approach conceives the ends of well-being and justice in terms of peoples' capabilities to function, i.e., their genuine opportunities to do and achieve the things they deem valuable in life) [20]. These things or states of intrinsic value, called functionings, include multiple diverse aspects of life such as being nourished, being sheltered, being mobile, being educated, being respected, being socially connected, etc. The capability approach helps shed light on the seminal question of what it is that actually matters for human well-being. By shifting the focus of justice from the distribution of goods (e.g., income and wealth) to the distribution of substantive opportunities, the capability approach emphasizes that the objective of justice should be to expand the opportunities of vulnerable people to attain well-being [21,22]. In doing so, it allows for an operationalization of justice that is able to factor in diversity in peoples' conception of the good life [22].

In any societal context, a genuine opportunity to realize a given functioning depends both on what an individual has (the resource or good) and what they can do with it [20,23,24]. What they can do is influenced by 'conversion factors', which are personal, social, and environmental aspects that help or hinder the realization of a desired functioning [25]. For example, the capability to seek medical treatment in order to stay healthy depends on the condition of the transportation infrastructure leading to the hospital (imagine during a flood, or a traffic jam). Scholars of risk, climate adaptation, and social justice argue that the capability approach provides a suitable framework for operationalizing justice concerns. They note that it is especially useful for expressing non-tangible impacts [26] and advocate applying it to monitor equality ("in terms of the distribution of substantive freedoms and opportunities among individuals and groups") and human rights ("in terms of the achievement of substantive freedoms and opportunities below a minimum threshold") [27]. Distributive justice requires us to make sure that all people are able to maintain essential capabilities (or functionings) above some acceptable threshold level [28].

2.4. Potential of ABM

Society is often characterized by unequal distributions of resources, opportunities, assets, and abilities among its members due to different personal, socio-political, and environmental circumstances. Actor heterogeneity thus forms an unavoidable backdrop upon which climate adaptation measures and responsibilities have to be carried out, along with being a driver of adaptive capacities and outcomes. Accounting for it is necessary to address concerns of 'corrective and compensatory justice' [29]. Climate adaptation policy is often informed by models, and for model-based policymaking to include considerations of justice the models must account for distributive inequities and differential vulnerability among people. However, most integrated assessment models (IAMs) that are used to evaluate mitigation and adaptation policies calculate their costs and benefits aggregated across different areas and actors [30]. This approach can easily miss the fact that an adaptation policy may offer aggregate benefits but engender unjust distributions of benefits and costs [31].

Agent-based modelling (ABM) is our modelling methodology for this study. ABM facilitates the depiction of heterogeneous and autonomous agents and their mutual interactions. Its intrinsic suitability to portray discrete yet interdependent entities makes it a most promising computational modelling method to represent complex social-environment systems whose macro-level behaviour emerges out of micro-level interactions [32]. This renders ABM particularly apt at shedding light on co-evolving system behaviour and emergent patterns that are not directly inscribed in the model conceptualization [33,34]. Such emergent phenomena can neither (easily) be derived through analytical methods, nor can they be predicted simply by examining the behaviour of the individual agents [35]. ABM provides a disaggregated multi-actor representational framework for the social-environmental entities and processes that constitute climate adaptation. As such it is our computational methodology of choice to simulate social-environmental systems and to study the evolving consequences of their interactions. We also note that the granularity afforded by ABM in characterizing societal entities and interactions comes at the cost of increased computational requirements [32].

ABM approaches have been used to explore the impacts of agricultural policy on land use, biodiversity, and ecosystem services [36,37]; to simulate the dynamics of urban water supply in order to outline sustainable drought management plans [38]; and to evaluate the economic impact of different flood resilience strategies on small and medium enterprises [39]. Accounting for ethics- and justice-based concerns in such models of climate change action, however, is a nascent pursuit, whose importance scholars increasingly highlight [40].

3. Model Description

This section describes the model conceptualization, purpose, and the distributive principles that have been formalized as interaction rules in it. Appendix B provides a model description using the Overview, Design concepts, and Details (ODD) protocol. The model is implemented in NetLogo 6.1.1 and can be found online (https://github.com/aashisjoshi/resource-capability-ABM, accessed on 25 September 2021).

3.1. Model Conceptualization

Our agent-based model aims to study the comparative performance of different principles of distribution using a broad, generalized conception of a social–environmental system. In the model we represent a stylized community of individuals, each of whom needs to obtain an essential capability to maintain their well-being by consuming resources from environmental systems (henceforth referred to as 'resource systems'). The individuals are differentiated in terms of an attribute which determines each one's ability to obtain the essential resource. This heterogeneity in resource access leads to differential capability attainments (and states of well-being) among community members. We operationalize different distribution principles as society–environment interaction rules in the model that outline the manner in which access to the resource is distributed among societal members. We then compare outcome patterns arising out of different principles of distribution in order to identify those that tend to achieve a fairer outcome pattern for heterogeneous actors.

An important constraint in the model is that resource systems suffer damage and degrade each time they provide the essential capability or resource to individuals. This means that they require restoration and maintenance or else their own state of well-being and productivity decline. That resource systems in the model incur damage through use or exploitation is meant to capture an essential feature of real-world systems (e.g., the economy) that convert materials and energy into goods and services: once consumed, a portion of the natural inputs leaves the system as pollution and waste [41]. These contaminate and degrade the natural environment, depleting its health and productivity. The generation of environmental externalities from conversion and consumption processes is a manifestation of the second law of thermodynamics, and forms an unavoidable constraint on limitless economic turnover [42]. Diminishing capability output from resource systems as degradation increases, along with increasing input requirements for repairing resource system damages, are meant to reflect this aspect of reality in our stylized model. In real world systems, recovery to the pre-consumption state may occur through ecological agents and processes, or human effort, or both. In any case, restoring degraded environmental systems requires an input of materials and energy.

A major requirement for the model is also that it should depict a finite system of interacting social–environmental entities, as the world itself is a finite system that allows neither limitless nor cost-free (in terms of environmental impact) resource consumption. In the model, this is achieved by having resource systems be able to provide for progressively lower amounts of capabilities or resources as they degrade. Such a constraint enables us to depict systems in which the interplay between resource consumption and environmental preservation is a zero-sum game and where a balance between the benefits and costs of these two forces is necessary for maintaining a functional society. The timescale represented in the model is arbitrary. We think that a temporally unspecific and unbounded conception is appropriate for our intention of focusing on operationalizing different principles of distribution to perform a comparative evaluation of their outcomes in a generalized social–environmental system simulation.

3.2. Theoretical Exploration as Modelling Purpose

We present a model of a generic social–environmental interaction process with a high degree of abstraction. The model lacks specific elements and processes that would characterize a particular type of real world social–environmental system. Instead, it captures an essential feature of human-environmental interactions, viz. resource consumption and environmental impact, taking place within the context of unequal access to resources among people. We avoid well-defined relationships with specific systems while trying to capture the essence of the dynamic that determines their state of well-being and stability. We choose such a simplified and abstract depiction so that we may formalize principles of distribution as interaction rules in a narrative that allows their effects to emerge quite directly. Our purpose with the model is to explore outcome patterns arising from different distributive principles of justice theory in a finite resource system. We do not seek specific insights applicable to a particular real-world system or community, but rather general ones on how one (operationalization of a) distributive principle may perform over another in securing well-being for individuals having unequal resource access. For that purpose, we aim for a generic structure that does not limit us to a single narrative but rather affords us the flexibility to draw analogies with various real world social–environmental systems where distributive justice is a concern. In leaving out the finer details that characterize specific climate adaptation scenarios, it also gives us room to consider which attributes and resources are key determinants of climate adaptation outcomes in different contexts, and what it would mean to put in place a given distributive principle in each one.

3.3. Model Narrative

3.3.1. Overview and Assumptions

Social Entities and Their Interactions

The stylized societal system depicted in the model consists of two entities: people and resource systems. Each individual person needs to fulfil an essential need to maintain their well-being. Resource systems are able to provide for this essential need; however, in the process they incur damages that accumulate and subsequently impede their potential to provide for the need. To maintain system performance, individuals must repair the damages, which requires expending some effort. This interdependency between individuals and resource systems means that the stability of the societal system against collapse requires the well-being of both entities. This allows us to comparatively study the effects of different distributive principles on system-wide outcomes, including when a principle may set the (primary) locus of distributive action at one or the other entity.

Capability Attainment and Access Potential

An individual's well-being is an outcome of their success in attaining this essential need, or capability in the language of the capability approach. This is evaluated as the moving average of their capability attainment over a certain number of past ticks. We choose a moving average as a suitable indicator of well-being, taking inspiration from real-life necessities such as nutrition; to be well-nourished does not require one to take in precise amounts of each nutrient during each meal, but rather to maintain average intake amounts over durations spanning hours, days or weeks, depending on the nutrient. In the model, success in attaining the capability from a resource system depends on an attribute that individuals possess and whose amount may vary from person to person. This attribute is termed the 'access potential', and it is meant to represent the relative number of resources that an individual is able to draw on in order to obtain the capability. The amount of access potential an individual possesses is positively correlated with another personal attribute called the 'social capital', which determines the size of their social network, i.e., the number of other individuals and resource systems they are linked with [43]. (Indeed, social capital may be regarded as the primary attribute that determines one's access to resources [44,45]; for our purpose, an exact positive correlation suffices.) An individual is able to interact only with entities they are linked with, such that a person's network size limits the number of resource systems they may call on to attain the capability, or the number of other individuals they may help or receive help from.

System State and Resource System Damages

When their capability attainment moving average is below a certain threshold, individuals will seek the capability by calling on the resource system unit in their network with the highest 'system state' value. The system state is a characteristic attribute of resource systems in the model that indicates their well-being, and their ability to provide for the capability is in direct proportion to its value. An individual's access potential and the system state of the resource system together determine the likelihood of their attaining the capability. These attributes may, therefore, be considered as abstractions of a personal and a socio-environmental conversion factor, respectively. When capability calls are successful and resource systems provide the essential need to people, the resource systems incur an amount of damage that is a function of both the amount of capability provided and the system state value. The damage function is chosen such that resource systems with higher system state values incur proportionately less damage than those with lower values.

Recovery of Resource Systems

We assume that capability attainment gives people the ability or means to carry out actions. In our stylized social system, individuals are able to repair damages to resource systems in their network if their capability attainment moving average is above a certain threshold. The extent of their ability or means to do so is limited during each tick by the value of their capability attainment moving average—a person has no more than this amount of means or 'effort' to expend on repair (or any other) actions. When an individual performs damage repair on a resource system unit, the amount of repair and recovery they are able to effectuate is in proportion to both the amount of 'effort' they have to expend and the system state of the unit. Resource systems that have higher system state values (i.e., are in better shape) are easier to repair and recover than those with lower values.

Accounting of Overall Changes and External Random Damage

The value of the system state attribute of resource systems takes into account both the damages and recoveries incurred over the preceding tick or time step. First, the total amounts of the damage and recovery experienced by each resource system unit from the individuals that link to it are each converted to a percentage impact figure by using a logistic function. The damage and recovery percentages are then added to determine the net system state change that occurred during the tick, and the new system state is updated accordingly. In addition to system state changes associated with society–environment interaction processes, there is also a random damage that resource systems suffer during each tick.

The random damage term is an abstraction of external stresses and disruptions such as climate change impact. Its effect is to add to the degradation that resource systems suffer, further impairing their capacity to provide for the essential need or capability. In each tick during a run the random damage may take on any value inside the limit specified, and with higher limits the damage term also makes a stochastic shift towards higher values. We impose damage values spread out over an increasing range across different runs in keeping with the real-world variability of environmental stresses and their trend towards greater severity due to climate change [46,47]. This helps shed light on which distributive principles are more likely to foster well-being under increasingly intense climate change impacts.

3.3.2. Overview of the System Dynamics

The primary dynamics captured in this model stem from the distributions of the access potential and system state attribute values that characterize people and resource systems, along with the relationships and interaction rules set between these entities that enable these distributions and their consequences to evolve. These distributions intend to represent societal heterogeneities and will set the stage for differential outcomes among individuals. An overview of the dynamics of this system is given in Figure 1.

In the process of providing the capability, resource systems incur damages which degrade their system state and must be repaired or else will lead to progressively lower levels of capability output. As individuals are better able to fulfil their capability need, they become better able to repair resource system damages. This allows resource systems' system state values to recover, improving their likelihood of providing the capability in the future. Higher capability attainment allows for the increased ability to participate in repair and recovery actions. However, at the same time it inflicts greater levels of damage on resource system units, thereby degrading their system state, which in turn lowers peoples' chances for capability attainment and subsequently their ability to contribute to damage repair. Adding to this dynamic is the nature or characteristic we have imposed on resource systems, viz. they incur greater operational damage at lower system state values while requiring progressively more means or 'effort' to repair and recover. A given model run results in system collapse when resource systems are unable to sufficiently provide the capability for individuals so that their average capability attainment moving average drops below a certain threshold. The likelihood of the system achieving a stable run depends on the interplay and balance between the need to attain the capability and its associated damages to resource systems, and the ability to repair or undo those damages.

3.3.3. Operationalizing Principles of Distribution

The access potential attribute of individuals is the means or 'currency' that enables them to obtain the essential need or capability from resource system units in their network. In our model we assign a random amount of access potential to each individual (in the range 0 to 1) to mimic a society in which there is an unequal distribution of resources and opportunities among different people and groups to achieve well-being. This heterogeneity among individuals sets the stage for unequal outcomes of well-being (measured in terms of the capability attainment moving average). Justice requires expanding the opportunities for vulnerable people to attain well-being, and the model allows us to try to do so in this stylized societal system by considering different principles by which access potential may be redistributed among individuals.

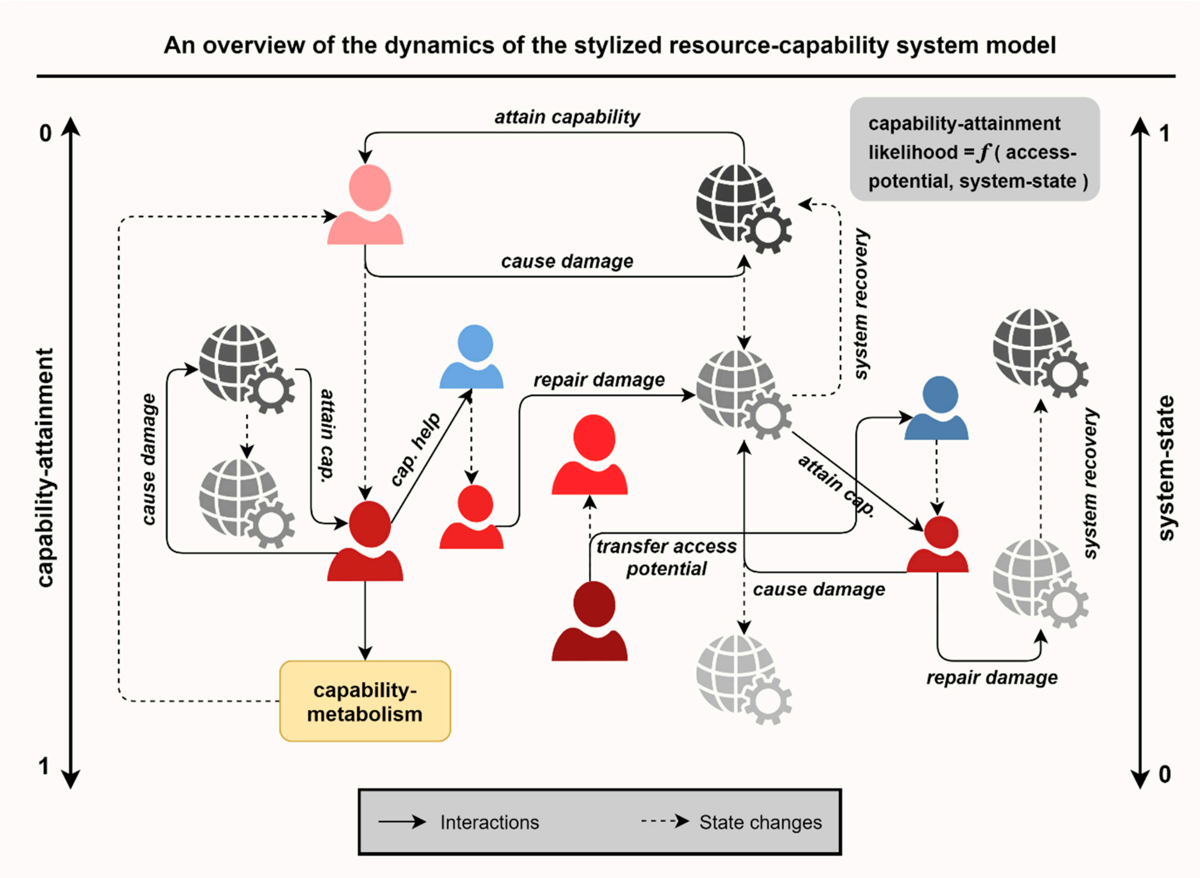

Figure 1. An outline of interactions in the stylized social–environmental system model. The colours and their shades indicate agent states: people with satisfactory capability levels are shown in red and those with unsatisfactory levels in blue. The darker the shade (for both people and resource systems) the higher (better) the state. The relative sizes of people suggest differences in access potential and social capital.

We attempt to formalize different principles of distribution in our agent-based model in order to evaluate the patterns of well-being that result from them. These principles are based on the distributive justice literature where they are generally discussed as coming from some central government, but here we implement them as rules guiding a self-organizing community. A comparative assessment of outcome patterns achieved from different distributive principles may indicate which ones are likely to fare better in helping secure well-being for people than others. This would highlight certain principles as having the potential to inform the design of a fair and just climate adaptation policy. In our agent-based model we operationalize the following distributive principles as rules governing interactions between system entities, alongside the baseline scenario in which there is no re-distribution.

- **Egalitarianism:** A strict egalitarian principle prescribes that each individual ought to have an equal number of resources and opportunities. In our model we operationalize this principle as a rule according to which all individuals in the societal system contribute all of the access potential they possess to a community fund. The access potential amount that has been pooled together is divided equally among people so that each individual has the same access potential with which to call on resource systems, giving them the same likelihood of obtaining the capability. This means that under an egalitarian redistribution in our model, all individuals have the same likelihood of obtaining the capability. This is a simplification we make, as realizing a capability in the real world depends not just on resource access but oftentimes on a multitude of social, political, and environmental conversion factors [27]. With this approach we are able to evaluate the effects of an egalitarian principle under (idealized) circumstances where conversion factors other than resource access potential are equal for everyone.

- **Sufficientarianism:** A sufficientarian principle requires that each individual be brought up to a minimum acceptable level of well-being before resources may be directed to other actions. Under this distributive principle in our agent-based model, individuals with at least an acceptable capability attainment will prioritize expending their means or effort to help others in their network with unacceptably low attainments by obtaining the capability from a resource system unit on their behalf. They will then devote the remainder of their means or efforts to repairing resource system damages.
- **Difference-proportionate sharing:** Under this distributive rule in the model, an individual who has been able to maintain their capability attainment above an acceptable threshold will transfer an amount of access potential to the person with the lowest average capability attainment in their network. The amount is set to be up to half the difference between the access potential amounts of the two individuals. The intent behind this rule is for individuals with satisfactory capability attainment levels to locally redistribute an amount of their access potential in proportion to the advantage they have over more vulnerable individuals.

We categorize capability attainment outcomes for individuals in three levels: desirable, acceptable, and unacceptable. We assess the performance of these principles of distribution based on their likelihood or tendency to enable more people to maintain desirable and acceptable average capability attainment levels and to minimize the proportion of individuals with unacceptable levels.

4. Experiment and Results

We ran a batch of experiments to compare outcome patterns that result from our implementation of three distributive principles and the baseline scenario with no redistribution. The batch consisted of 4000 model runs spread over these four rules for allocating the access potential attribute, so that for each rule we have roughly 1000 runs and outcomes. The combination of input parameter values is likely to be different for each run as they are sampled randomly from within the ranges given in Table 1. It is important to note that these are abstract relative quantifications for drivers of model behaviour meant to simplify the assessment of emergent outcome patterns and do not represent real physical quantities.

Table 1. Model setup parameters in the stylized resource-capability system model.

Model Parameter	Description	Value or Range in Experiment
Number of people	The population size of the stylized social system.	200
Number of resource systems	The number of resource system units that provide the essential need or capability.	12
Access potential	The attribute that determines an individual's chances of attaining the capability, and the object of redistribution.	[0.00–1.00]
Random damage limit	The maximum amount of periodic damage not induced by resource consumption that resource systems may suffer.	[0.1–33.34%] of system state
Resource system operation threshold	The value of a resource system unit's system state below which it ceases to function.	0.20

Table 1. *Cont.*

Model Parameter	Description	Value or Range in Experiment
Principles of distribution	Principles we formalize as rules according to which the access potential is allocated or shared.	no redistribution; egalitarian; difference-proportionate; sufficientarian
Time limit for each run	The maximum number of time steps that each run is allowed to last.	3000 ticks
Capability attainment (moving average) levels: • Desirable; • Acceptable; • Unacceptable.	These ranges for capability attainment values are used to categorize and assess the well-being of individuals.	• 0.50 <= x • 0.25 <= x < 0.50 • 0.25 > x
Capability unit	The amount of capability that can be obtained from a resource system at each call (attempt).	0.75

We settled on 3000 ticks as a sufficient time limit for model runs after observing that plotting the fraction of runs that have collapsed against their duration yields a saturation curve, as in Figure 4E. This indicates that the vast majority of runs that are stable up to the 3000-tick mark will remain stable beyond, thus little added insight would be gained by allowing them to continue.

4.1. Redistribution of Access Potential

The distributive principles we have transcribed as interaction rules in our ABM reshape the allocation of access potential in the community, and, therefore, drive differential patterns of capability attainment and impact on resource systems. Figure 2B illustrates the relative extent to which our principles address unequal distribution of access potential. As we expect, the access potential amount varies among individuals without redistribution. An egalitarian principle ensures that differences in access potential among individuals are eliminated, whereas the difference-proportionate sharing rule reduces differences but does not remove them. (In our implementation of the latter rule, redistribution stops at higher damage values when people become unable to fulfil their own capability need). These principles do not, however, affect the global mean access potential, as the total access potential in the community is a conserved quantity and the principles only rearrange its distribution. This we can confirm from Figure 2A.

4.2. Outcome Indicators

We assess the comparative performance of these principles of distribution using indicators such as the percentage of people who fall in the desirable, acceptable, and unacceptable ranges of capability attainment; the minimum global mean capability attainment during a given run; the mean system state of resource systems; the amount of resource system repairs carried out; and the fraction of runs that collapse. These are some of the model's output variables. We want to know which distributive principles tend to enable a higher fraction of the population to secure desirable and acceptable levels of capability attainment compared with the baseline scenario while lowering the number of people in the unacceptable range. This would help us identify which distributive principles (and their operationalizations) are more conducive to justice than others. At the same time, we are interested to find out which ones help foster stability in our stylized social system. For this, we compare the fraction of model runs that collapse under each principle.

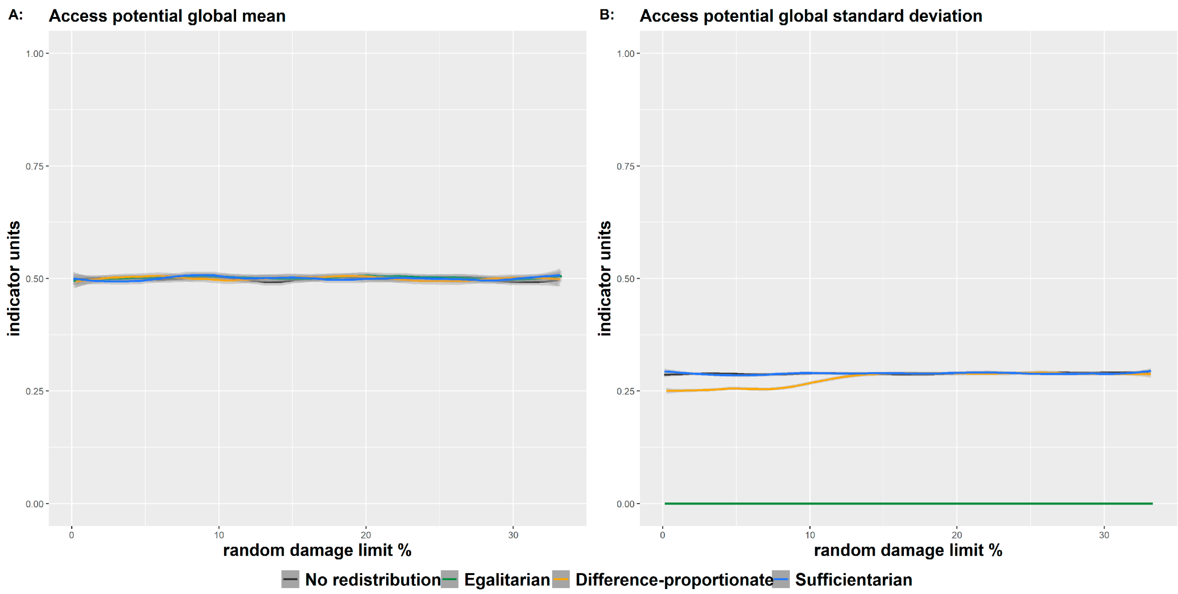

Figure 2. Distribution of the access potential under different principles.

4.3. Outcome Patterns

Figure 3 shows the relative performance of different distributive principles in facilitating capability attainment. Experimental results without fitted lines are shown in Appendix A.

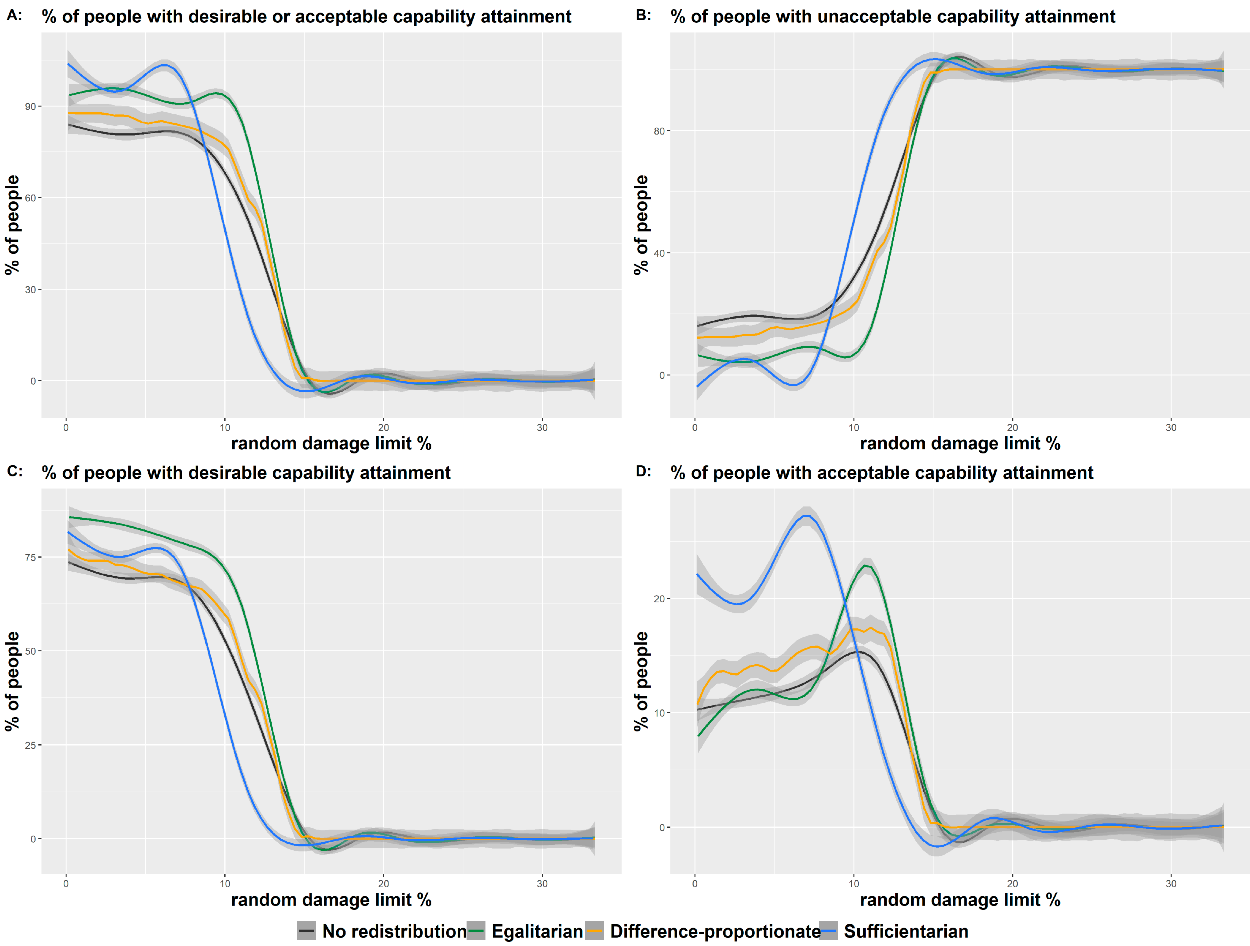

Figure 3. Capability attainment patterns under different distributive principles.

We observe the following outcome patterns:

- The steep descent to zero of all four satisfactory capability attainment curves in Figure 3A shows that none of the four different modes of allocating the access potential is able to ensure system stability beyond a certain threshold value of the random damage limit parameter. This value differs across the modes, with the egalitarian one able to tolerate higher damage limits best, and (our implementation of) the sufficientarian one worst. These patterns emerge due to the extent of resource system damage repair that each distributive principle facilitates, which Figure 4D highlights.
- The egalitarian principle achieves the best results overall, generally increasing the fraction of people with a desirable capability attainment and decreasing the unacceptable attainment fraction. It is a clear improvement on the baseline scenario in which there is no redistribution of the access potential.
- The sufficientarian principle improves capability attainment at lower random damage values but performs significantly worse as the random damage value increases. It also results in the highest fraction of runs that end in collapse.
- The difference-proportionate rule improves capability attainment and run stability over the baseline no-redistribution scenario, but not to the extent that an egalitarian redistribution would allow.
- In Figure 4C, we see these patterns reflected also in the relative values for the minimum global mean capability attainment. The egalitarian redistribution, and to a lesser extent the difference-proportionate one, tend to raise it over values reached in the baseline case. The sufficientarian principle is only able to improve this at lower random damage values.

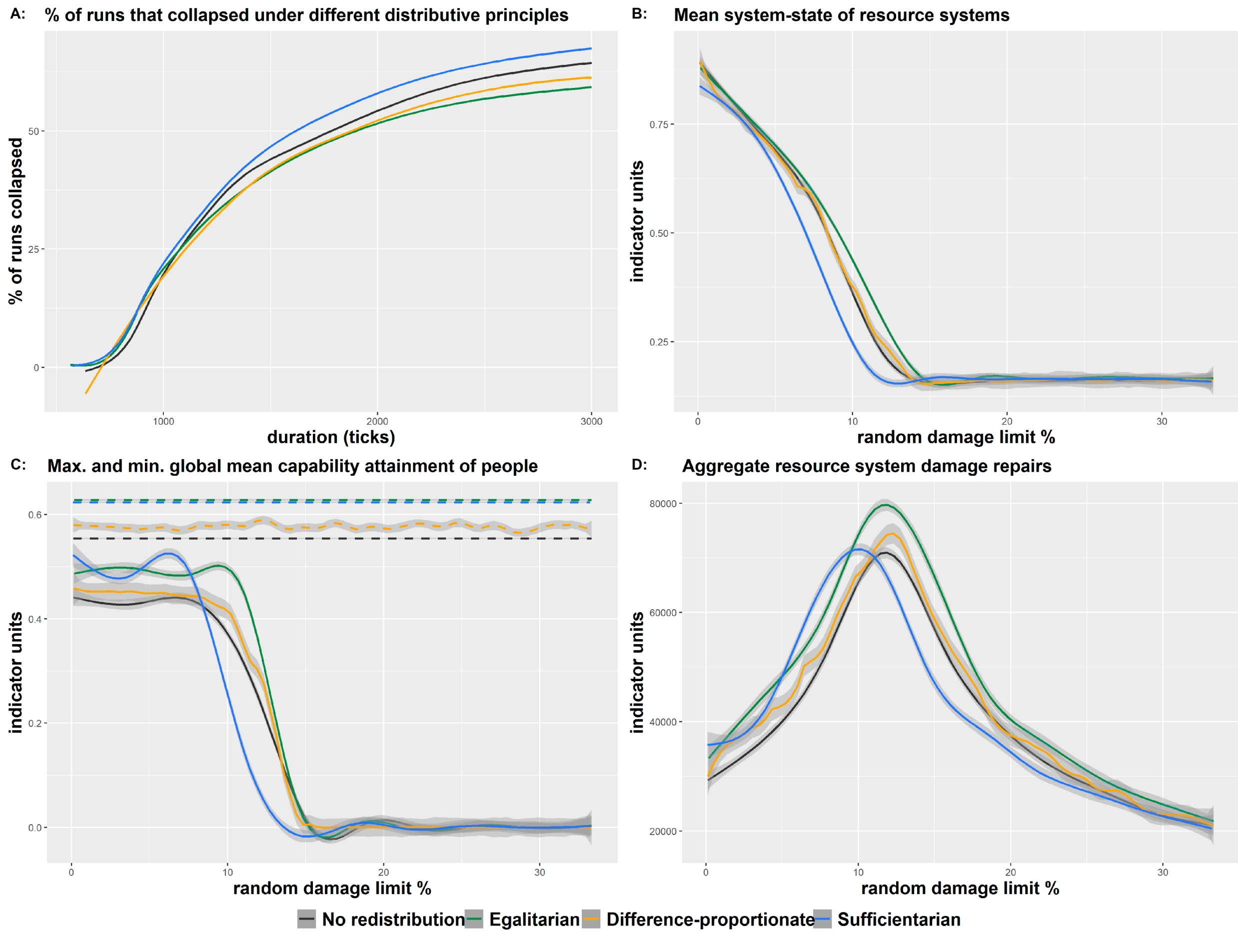

Figure 4. Other performance indicators: fraction of runs collapsed, mean system-state, maximum and minimum global mean capability attainments, and extent of resource system damage repairs across the four distributive rules.

4.4. Baseline Scenario: No Redistribution

To make sense of the outcome patterns that each distributive principle yields, it helps to first understand what is happening in the baseline scenario where there is no distributive principle in place. Here, access potentials differ among people but stay the same for an individual throughout a given run. Individuals with higher amounts are able to attain the capability from resource systems more consistently than those with lower. Another factor that determines this consistency is the system state of resource systems, which evolves according to the number of damages accumulated and repairs performed. With low values of the random damage limit parameter, enough people are able to attain the capability to be able to sufficiently repair damages incurred by resource systems. In runs with higher random damage values; however, resource systems suffer significantly greater damages due to this term. As damages accumulate, there is a gradual decline in resource systems' ability to provide for the capability, and as a consequence, a lower amount of means or effort available for repair. There is a certain random damage limit value beyond which there is a sharp increase in the percentage of people with an unacceptable capability attainment. This indicates the point at which resource system damages overwhelm the capacity to repair them, which anticipates the social system's collapse.

4.5. Egalitarian Principle

The overall improvement in outcomes achieved with an egalitarian principle is a consequence of everyone having the same access potential, and, therefore, equal likelihood of attaining the capability. The effect of redistributing access potential equitably is that while the likelihood of attaining the capability in a given tick is lowered for those who initially had higher-than-average access potentials; it is improved for those who started off with lower-than-average amounts. The balance shifts towards an overall improvement in capability attainments under this principle due to better odds for resource systems to recover, as evidenced in Figure 4D. Those who would have been able to attain the capability at a higher frequency without redistribution are now restricted to a more modest capability attainment level, which means their contribution to resource system damages is also reduced. At the same time, those who would not have been able to attain the capability with their original lower access potentials are now able to more consistently do so, so that there are now more people who can contribute to repairing resource system damages than in the baseline scenario. These processes together result in better system state values, and, therefore, an improved capacity of resource systems to provide for the capability, which ultimately translates into better capability attainment outcomes.

4.6. Sufficientarian Principle

For our quite altruistic interpretation of the sufficientarian principle, we find an increase in the percentage of people attaining the capability at the desirable level and a corresponding decrease in the unacceptable level at low random damage values. For runs with higher random damage values, however, this principle performs markedly worse, as we can see in Figure 3A–D. We observe this pattern because in each tick, those who have been able to attain the capability will then obtain it on behalf of a person with insufficient access potential. Doing so helps the less well-off attain the capability more often, but at the same time it requires effort from those who provide this help, which would otherwise be spent on repairing resource system damages. As we quantify the capacity to repair damages in terms of an individual's current capability attainment average, which is itself positively correlated with their access potential, in our setup individuals with lower access potentials are generally unable to effectuate the same amounts of recovery as those with higher. The effect of having the well-off prioritize spending their effort to help others attain the capability over repairing resource system damages, then, is an overall loss in the collective restorative capacity. There is less repair activity being carried out in this scenario, and resource systems do not recover to the same extent as under the other principles. The system is, therefore, bound to be less tolerant to higher random damage values and also collapse earlier than under other distributive principles.

4.7. Difference-Proportionate Rule

Finally, we find that the difference-proportionate rule tends to improve outcomes compared with the baseline scenario but falls well short of the egalitarian principle's performance. Under this rule, an individual with at least an acceptable capability attainment value will transfer to another with an unacceptable value an access potential amount proportionate to the access potential advantage they have over the recipient. We may think of such a redistributive mechanism as being akin to a progressive tax on wealth, for example, but which in our implementation takes place as a stochastic person-to-person transaction. This means that a variable amount of access potential is redistributed in the community in each time step, which is statistically likely to be insufficient to eliminate differences among people as the egalitarian principle would. The effect of having varying transfer amounts is that those from very well-off individuals to the less well-off are likely to be large enough to enable the recipient to attain the capability, whereas those between more evenly matched donors and recipients may not. For this reason, we observe lower efficacy with this rule in achieving a desirable or acceptable capability level and fewer damage repairs relative to an egalitarian distribution, whereas it is still an improvement over the no-redistribution baseline scenario.

5. Discussion

In this work we operationalized different principles of distribution as interaction rules in a stylized agent-based model representation of a community to assess their relative potential to secure well-being. We depicted an abstract social–environmental system subject to some abstract climate change impact, where individuals with different capacities to access a resource seek to achieve an essential need or capability through resource consumption at the cost of environmental degradation. We aimed for insight on which rules for reallocating access to the resource might improve well-being outcomes in the community and limit environmental degradation so as to avoid system collapse. In doing so, we take some first steps towards accounting for ethical and justice concerns in model-based approaches to climate adaptation planning and policy-making.

Our experimental results suggest that an egalitarian distribution is most conducive to attaining satisfactory capability levels and system stability (when all conversion factors except for resource access potential are same for everyone). Under our basic assumption that resource consumption also leads to environmental degradation, it performs best as it moderates consumption from the most well-off and better facilitates the recovery of degraded resource systems. Egalitarian approaches are often thought to be vulnerable to the levelling-down objection, which challenges the egalitarian principle on the grounds that the extent of redistribution it requires may reduce inequality but without improving overall welfare [48]. Within a finite resource system in which a higher consumption capacity equates to higher environmental impact, however, our results show that eliminating inequality can in fact promote improved welfare levels. This insight questions the validity of the levelling-down objection against egalitarian redistribution given limits to nature's capacity to provide the resources needed to maintain welfare.

Our altruistic conception of sufficientarianism is an improvement over the baseline no-redistribution scenario at lower random damage values but leads to worse outcomes at higher ones. This is because our operationalization entails a greater societal commitment to the well-being of the less well-off than to repairing resource system damages, and so it limits the means available for repair. We may conclude that designing some sufficientarian-based policy requires coordination about how to bring people to the sufficiency level. The difference-proportionate rule achieves intermediate results to the baseline and egalitarian cases. Here, variability in the quantity of access potential redistributed means that overall, the opportunities for attaining the capability and repairing resource system damages are lower than with an egalitarian allocation.

5.1. Model Analogies with Real World Situations

A reflection on what kinds of real-world systems and societal aspects might form suitable analogies for such a stylized model is warranted here. As indicated earlier, the model depicts a generic social–environmental system in which consumption goes hand-in-hand with resource system degradation. It may, therefore, claim to be a stylized representation of any human-environmental interaction process that creates economic or social value using natural resource inputs while emitting waste and pollution that need to be cleaned up, or causing degradation that requires restoration or replenishment so that the system may continue to function.

With this outline in mind, we may first connect the model's structure to the climate crisis in broad and general terms. The driver of this crisis is greenhouse gas emissions from economic activity, and as they accumulate, they cause a progressive degeneration in the state of the biosphere. We may regard the individual agents depicted in the model as socio-economic entities—e.g., households, communities, or nations—that cause emissions as they process and consume natural resources. If we interpret the access potential as the entities' economic or processing capacity, then its value would translate proportionately as their environmental impact. The resource systems would collectively represent the biosphere itself. Emissions degrade the biosphere, gradually diminishing its capacity to provide essential resources and ecosystem services. Seeking distributive justice by reallocating access potential would imply transferring economic capacity from the well-off to the less well-off entities.

A more specific analogy could be with a community of farmers and their agricultural lands as resource systems. The farmers derive their livelihood and well-being by growing crops on these lands, for which they need water. We may consider that the access potential attribute represents the amount of water that a farmer has access to or can afford. Each farmer's agricultural yield depends on the amount of water they are able to use for their crops, and heterogeneity in this attribute among farmers results in unequal yields and consequently differential well-being outcomes. The soil fertility declines after each harvest and needs to be replenished. The resource system repair process implemented in the model may be thought of as a collective accounting of such soil-replenishing efforts. In traditional and organic systems of agriculture, this may take place through a combination of human actions such as applying manure and compost, diversifying and rotating crops, etc., and nutrient cycling processes carried out by ecological entities and their interrelationships. In industrial and intensive agricultural systems, restoring soil fertility is a matter of applying artificial fertilizers, which farmers have to purchase out of the earnings from their harvest. If we focus on the industrial agriculture analogy, as different farmers have different amounts of water they are able to access, their harvests, earnings, and, therefore, their ability to invest in fertilizers to replenish lost soil minerals are unequal. Redistributing the access potential would in this case mean reallocating access to water among the farmers.

5.2. Contributions and Implications

This work offers three main contributions:

- It adds a novel perspective to the nascent challenge of how to evaluate justice outcomes in model-based approaches to climate adaptation planning and policymaking. Our model presents a basic social–environmental system structure on which to operationalize distributive principles from justice theory as interaction rules. It provides a quantitative and stochastic testing ground to explore the consequences of certain normative ethical principles on general well-being outcomes. In doing so, our work contributes to extending the potential of ABM to account for ethical concerns in a climate adaptation context. It is also a small step towards bridging the gap between the realms of social systems modelling and applied ethics.

- Model-based representations of social–environmental systems must account for inherent systemic uncertainties to the extent appropriate for their purpose. For our model we opt for a simplified, generic representation that eschews context-specific details in favour of capturing the fundamental process that underlies society–environmental interactions: resource consumption leading to environmental impact. In whittling down societal entities and interactions to such basic forms, we essentially construct an idealized system in which the effects of a distributive principle manifest without being amplified or diminished by various sources of uncertainties. While our model is idealized and abstracts from some arbitrary contingencies, it does recognize the finiteness of ecosystems and is thereby more consistent with approaches that are built on the idea of planetary boundaries [49]. We present this as a useful approach for performing a broad quantitative exploration of the relative merit of different distributive principles in a climate adaptation context.
- It contributes to the discussion on distributive justice as a societal precondition to ensure equitable and successful adaptation outcomes among differentially vulnerable people and groups. The generic social–environmental system of the model facilitates a comparative assessment of the impact of different principles of distribution on well-being outcomes in a finite-resource system. It gives insight into the types of distributive policies that are most likely to foster effective and fair climate adaptations, and how best to reallocate access to essential resources in society to that end.

What implications could the outcome patterns we observe have for real-world climate adaptation situations? By depicting a finite resource system in which well-being is derived from resource consumption coupled with environmental damage, we set a constraint against unlimited and impact-free increase in welfare levels. In a world with such constraints, we may infer that redistributing consumption capacity tends to favour fairer and more durable outcomes than without redistribution. Outcome patterns and effectiveness vary among principles, but redistribution generally helps level the playing field for achieving well-being and facilitates greater participation in restorative or adaptive actions. It moderates consumption by the better-off and its resulting environmental impact, thus it is more conducive to a stable environment that is able to provide for essential needs. These insights seem immediately relevant to address the global predicament of rising and deeply unequal resource consumption driving the climate and ecological breakdown. From our interpretation of sufficientarianism, we also gain the nuanced insight that remedying unequal capacity to attain well-being via redistribution might be more effective than redirecting efforts to remedy unequal attainment, the end product, itself. Our work provides model-based quantitative support for distributive policies as a means to enable effective and fair outcomes among unequally vulnerable people and groups under the spectre of intensifying climate change impacts.

Some applied ethicists contend that redistribution is difficult to pursue in an international climate policy because wealthy nations are unlikely to agree to measures that diminish the welfare of their current citizens [50,51]. If the goal of climate policy is to increase welfare for current and future citizens as a whole, however [52], then our model helps build a case for redistributive action. Although we do not account explicitly for intergenerational justice, our model relates resource consumption rates to the severity of their environmental impact using a simplified mechanism. We find that the manner in and extent to which different distributive principles address unequal consumption capacities has a strong bearing on their potential for moderating environmental impact and promoting restorative action. This potential translates into the likelihood for long-term system stability against collapse, which is indicative of environmental systems that are able to provide for essential needs now and in the future. The general insight we gain from our model is that a redistributive climate policy would likely improve the odds of achieving just outcomes for both current and future peoples, with satisfactory welfare outcomes and stable runs both most probable under an egalitarian reallocation. This work suggests that redistribution is worth pursuing in climate policy if we care for the well-being of future generations.

5.3. Limitations and Future Work

In our agent-based model, we portray a spatially homogeneous society in which an individual's location, and consequently the people and resource systems in their network, is set randomly without regard to the access potential they possess. In reality, people and groups with comparable access potentials may be geographically closer and socially better linked than those with quite different amounts. This could engender geographically unjust distributions of climate adaptation benefits and burdens. This limitation of our model stems from the abstract representation we have chosen for this attribute. Future work could seek to quantify it (or its equivalents) to reflect key resource access-granting attributes and their patterns in the climate adaptation scenario we are interested in modelling.

A second limitation is that we do not account for the subtleties of human behaviour and decision-making when operationalizing principles of distribution as interaction rules. We simply assume a universal inclination to comply with them. However, behavioural drivers such as the tendency for cooperation or competition can be variable, and changes in them are pivotal for shaping the course and outcomes of climate action. These are aspects of reality we may want to represent in subsequent work.

Our goal with this work has been to facilitate a broad quantitative evaluation of welfare outcomes in terms of justice standards, and to advance the discussion on the potential of distributive justice as a cornerstone of climate policy. The next steps will include embedding a more concrete contextualization in the model by situating its resource consumption-environmental impact mechanism in a richer narrative where actors may choose between alternative adaptive responses based on contextual realities and a set of relevant criteria. We also intend to include the consideration of different grounds for distributing costs and benefits based on unequal vulnerabilities, contributions, and capacities. This then allows us to explore the conditions necessary for communally beneficial climate adaptation projects to materialize over personally beneficial outcomes that are not accessible to everyone and may exacerbate climate injustice. The insights gained may help us outline effective and just strategies for allocating climate adaptation responsibilities in society.

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Appendix A. Overview of Experiment Results

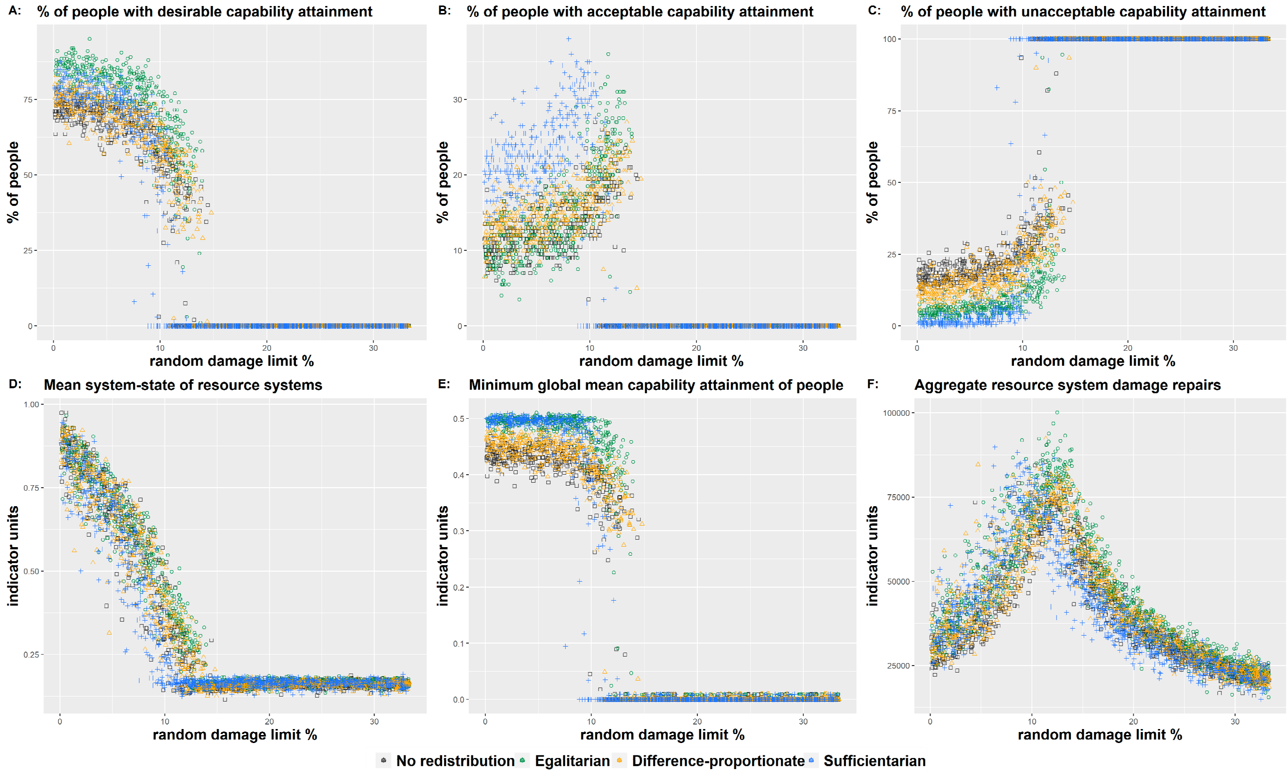

Figure A1. Model outcomes without fitted line.

Appendix B. ODD Model Description

Table A1. Overview, design concepts, and details (ODD) for the stylized resource-capability system model.

Overview	
Purpose	To perform a comparative evaluation of the effects of different principles of distribution on the ability to attain an essential need in a stylized social–environmental system.
State variables and scales	There are two agent (turtle) types: individuals and (social–environmental) resource systems. Individuals possess an attribute called 'access potential' which differentiates them from one another. In the language of the capability approach, the access potential may be thought of as a personal conversion factor that determines one's ability to attain an essential need. In the model we also consider another attribute called 'social capital' as being completely correlated with an individual's access potential attribute. An individual's social capital determines the number of resource systems and other individuals that they may interact with. Resource systems are characterized by their 'system state', an indicator of their health and capacity to provide the essential need. This attribute variable may be thought of as a socio-environmental conversion factor. The values of the access potential of individuals and the system state of resource systems both range from 0 to 1. Access potential values do not change over time except when a distributive principle is implemented. The system state attribute of resource systems evolves as they provide the essential need to people and in the process accrue damages that need maintenance and repair.

Table A1. *Cont.*

Overview	
Process overview and scheduling	Setup: - Individuals and resource systems are initialized with random access potential and system state values. - Individuals are linked with resource systems and other individuals; the size of each one's network depends on their social capital attribute. Go: - Individuals assess (or sense) their well-being in terms of their capability attainment running average. - If this is below a certain threshold, the individual will call on the resource system unit in their network that is in the best state and seek to obtain the capability (essential need). - The resource system unit suffers some damage as it provides the capability, which degrades its system state and potential to provide the capability. The system state is evaluated each tick. - When their capability attainment running average is above a satisfactory threshold, an individual will contribute to maintaining resource systems by spending effort to repair the damages these systems have accrued. - Under certain distributive justice principles, individuals with satisfactory levels of capability attainment will help individuals in their network with inadequate access potential to obtain the capability or essential need from a resource system unit before contributing to maintenance and repair of resource systems.
Design concepts	
Theoretical and empirical background	Actor heterogeneity in society entails unequal vulnerability to climate change impacts, and means that some people and groups will be better able to adapt than others. Justice requires a fair and equitable distribution of risks and benefits of adaptation actions across society (including as a means to foster resilience). Different principles of distribution are operationalized and evaluated against one another in terms of their effect on peoples' ability to fulfil their essential needs, or capabilities in the language of the capability approach.
Individual decision making	For each tick, individuals evaluate their state of well-being. If their capability attainment running average is below a certain threshold, they will call on a resource system unit in their network to try to obtain the capability (or essential need). If it is above the threshold, the person will contribute to repairing damages incurred by resource systems, or to help ensure that people with inadequate access potential are also able to attain the capability (essential need), depending on the principle of distribution followed.
Learning	None.
Individual sensing	Individual agents are aware of the states of other individuals as well as resource systems in their network. This allows them, for example, to select the most needy individuals in their network to help, or to perform repairs on the most damaged resource system unit(s).
Individual prediction	None.
Interaction	Individuals interact with the resource system units and other individuals in their own network. They call on resource systems to obtain the essential need (capability) and to repair the damages they have accumulated. Under certain principles of distribution, they seek out individuals to help and do so by sharing some of their access potential or by obtaining the capability on their behalf.
Collectives	Individuals and resource systems are linked in networks. However, each individual has their own network, and a person in that network is unlikely to have the same network for themselves as well.
Heterogeneity	Individuals possess different amounts of the access potential attribute, which sets up unequal capacities to obtain the essential need from resource systems.

Table A1. *Cont.*

Design concepts	
Stochasticity	The following elements are stochastic in the model: - The individuals and resource system units to which an individual is connected or linked. - The value of the access potential attribute for each person. - The initial system state value for each resource system unit. - The process of calling on resource system units and obtaining the capability or essential need is probabilistic.
Observation	The model provides the following output: - The capability attainment of individuals, which indicates their state of well-being. - The system state of resource systems, also an indicator of their well-being and capacity to provide the essential need.
Details	
Implementation details	The model is implemented in NetLogo 6.1.1. The following functions are used: - Likelihood of an individual attaining the essential need (capability) from a resource system unit P (capability attainment) = access-potential * (system-state) ˆ (1/2) - Capability attainment running average of individuals capability-attainment-running-average = Mean (capability-attainment, 5 most recent ticks) - Damage incurred by a resource system unit when providing the capability system damage with capability output = capability-output * (1 − (system-state) ˆ (1/2)) - Recovery of a resource system unit with maintenance and repair effort from individuals max. maintenance effort by individual = capability-attainment-running-average system recovery with maintenance effort = maintenance-effort * (system-state) ˆ (1/2) - Random damage to resource system units random damage = [0, random-damage-limit] - System state of resource system units damage-impact = 1/(1 + exp (− (total-system-damages − (minimum-system-damage-this-run + system-damage-range-this-run/2)))) repair-impact = 1/(1 + exp (− (total-system-repairs − (minimum-system-damage-this-run + system-damage-range-this-run/2)))) net-system-state-change = (− damage-impact + repair-impact − random-damage) If net-system-state-change >= 0: system-state = system-state-old + (1 − system-state-old) * net-system-state-changeIf net-system-state-change < 0: system-state = system-state-old * (1 − (− net-system-state-change/100)) There are three different rules according to which the access potential may be (re-)distributed in the model, besides the 'baseline' scenario in which there is no re-distribution of access potential among individuals. - Strict egalitarian sharing over entire community Each individual contributes their entire access potential into a communal fund from which each then withdraws an equal amount of access potential with which to try to attain the essential need (capability).

Table A1. *Cont.*

Details	
Implementation details	- Difference-proportionate sharing in smaller networks An individual with a satisfactory level of capability attainment will share with the individual in their network who has the lowest capability attainment running average an amount of their access potential in proportion to the difference between the access potentials of the two individuals. - Sufficientarianism principle An individual with a satisfactory level of capability attainment will, before repairing damages on resource systems, contribute their effort to helping individuals in their network having unacceptable capability attainments obtain the essential need from a resource system unit (in order to try to ensure that all individuals reach a certain minimum threshold of well-being).
Initialization	Individuals and resource systems are set up and linked; the number each individual is linked with is based on their social capital attribute value. Each individuals is assigned an access potential value from 0 to 1.
Input	Number of individuals and resource system units; desirable, acceptable, and unacceptable capability attainment thresholds; distribution principles for the access potential attribute; extent of random damage (as a representation of external stresses such as a climate change impact) suffered by resource systems.
Submodels	None.

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