Space-Time Discounting in Climate Change Adaptation

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Abstract

Discounting is traditionally interpreted as the technique for comparing the values of costs and benefits which occur at different points in time. It endeavors to incorporate how humans trade off values to be received in the future versus value received immediately into economic analysis. Interpreted as such, discounting neglects important spatial influences on how values are compared, thereby hindering cost-benefit analyses of climate change adaptation. In this article, we present new theory on space-time discounting and use it to analyze aspects of how humans adapt to climate change. Three climate change adaptation cases are considered. First, analysis of crop indemnity payments to farmers shows that failure to discount across space and time yields inaccurate evaluations of adaptation projects. Second, adaptation efforts of the Commonwealth of Nations show irregular patterns of international cooperation that suggest spatial discounting of adaptation which are not found in temporal discounting. Third, the nexus between climate change, migration, and conflict shows how various forms of space-time discounting can influence whether climate change and migration will lead to conflict. Collectively, these cases demonstrate the analytical power of the space-time discounting theory and also show how the complexity of climate change adaptation can challenge and strengthen this theory. Finally, this article's analysis demonstrates that proper discounting must include space as well as time.

Key Words: adaptation; climate change; Commonwealth of Nations; conflict; cost-benefit analysis; crop indemnity; discounting; migration

1. Introduction

Discounting traditionally refers to a process used to compare the values of costs and benefits that occur at different times within a cost-benefit analysis (CBA). It measures, among other things, willingness to put off a benefit today in return for one in the future. For example, a $1000 benefit that comes in ten years is worth $905 in present dollars if discounted at a 1 percent annual rate or $368 at a 10 percent annual rate.[1] The effect of discounting increases as the costs and benefits fall further into the future. Indeed, at even modest discount rates, virtually all distant-future costs and benefits appear negligible, prompting vigorous discussion of inter-temporal and inter-generational distributive justice (Lind 1982; Laslett and Fishkin 1992; Portney and Weyant 1999; Weisbach and Sunstein 2007; Zeckhauser and Viscusi 2008).

Discounting has figured prominently in CBAs of long-term societal issues. Many of these issues have been related to the environment, with climate change getting much of the attention. Indeed,

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[1] $\$1000 * \exp(-0.01\text{yr}^{-1} * 10\text{yr}) \approx \$905$; $\$1000 * \exp(-0.1\text{yr}^{-1} * 10\text{yr}) \approx \$368$.

the role of discounting in climate change CBAs made international headlines in recent years in the aftermath of the *Stern Review* (Stern 2007). The *Review*, produced by a UK-sponsored team led by former World Bank Chief Economist Nicholas Stern, was heavily criticized by other economists and researchers, primarily for how it handled discounting. Though the *Review* itself was much broader, the critiques focused on the *Review's* approach to greenhouse gas mitigation (Neumayer 2007; Nordhaus 2007; Spash 2007; Weitzman 2007; Barker 2008; Hasselmann and Barker 2008; Dasgupta 2008; Jaeger et al. 2008; Mendelsohn 2008; Quiggin 2008; Sterner and Persson 2008; Weyant 2008; Yohe and Tol 2008; an exception is Pielke 2007, who focuses on impacts and adaptation). The *Review* derived discount rates from ethical principles roughly corresponding with classical utilitarianism. For example, criticizing this discounting, Nordhaus (2007) argues that the *Review* should have matched discount rates to market interest rates so that the resulting mitigation policy would be more efficient and better matched with how society discounts. Meanwhile, Dasgupta (2008) argues that the *Review*'s discounting leads to mitigation policy that places insufficient emphasis on the interests of the poor. But while this discounting debate is diverse, it focuses on discounting across time, neglecting important spatial aspects of discounting.

In this article, we deviate from the customary discourse on discounting in climate change in two key regards. First, we focus not on mitigation of emissions but on adaptation to climatic changes. Though the existing discounting debates have generally avoided adaptation, we argue that discounting is central to adaptation decisions and deserves more robust treatment. Climate change adaptation refers to efforts to minimize damage or seize opportunity from the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (Watson et al. 2001, p. 365). Note that this definition is based on costs (harms) and benefits which are not necessarily monetary or even human. Money is undoubtedly important to climate change adaptation. But other factors matter too. Innovation and technical change, knowledge, human capital, and governance structures, among other things, all have been identified as influential to successful adaptation (Adger et al. 2007). Efforts to convert these factors into a common monetary numéraire (unit of analysis) mask the full complexity of the adaptation process. For this reason, the possibility of performing CBAs with non-monetary numéraires is central to the analyses in this paper.

There have been relatively few CBAs of climate change adaptation. See Adger et al. (2007, p. 724-727) or Stage (2010) for reviews. The lack of adaptation CBAs derives largely from the complexity of adaptation scenarios. Of the CBAs that have been conducted, most use a monetary numéraire. This includes the agriculture sector analyses of Adams et al. (2003) and Butt et al. (2005) as well as the Yohe and Schlesinger (1998) and the Ng and Mendelsohn (2005) analyses of adaptation to sea level rise. An exception is Easterling et al. (2003), who measure benefits to adaptation in the agriculture sector in units of crop yield.

Adaptation, like mitigation, involves investments that will play out over a long time period. Thus, several of the adaptation CBAs incorporate some treatment of temporal discounting. For example, Yohe and Schlesinger (1998) use a 3 percent annual monetary discount rate; Ng and

Mendelsohn (2005) use a 4 percent rate. However, these treatments of discounting have not provoked anything near the strong discounting debates found within the mitigation literature.

The second way in which we deviate from the customary discourse on discounting in climate change is by considering discounting across space as well as time. The traditional time-only conception of discounting neglects important spatial attributes of how people make (and how people should make) discounting decisions. The need for the handling of space in discounting is particularly acute in many aspects of climate change adaptation, such as the complex spatial heterogeneity of climate change impacts, in the evaluation of adaptation projects, and of cooperation and conflict in adaptation efforts. Indeed, one reason we focus on adaptation is because the complexities of adaptation demand more complex discounting treatments than are commonly offered. Thus the analysis of integrated spatial and temporal discounting in climate change adaptation offers advances in our understandings of both adaptation and discounting, advances that may facilitate further CBAs of adaptation and other complex nature-society phenomena.

While several of the previous adaptation CBAs consider spatial heterogeneity in costs and benefits (such as in agricultural land productivity), none explicitly include treatments of spatial discounting. Instead, the studies generally treat a unit of money (or other numéraire) as equally valuable regardless of where they occur. We illustrate the role discounting in adaptation through discussion of three cases. The first case is an example of the evaluation of an adaptation-oriented government program focusing on the use of crop indemnity payments. This case illustrates how failure to discount across space and time can yield inaccurate evaluations. The second case is of cooperation among nations with regard to adaptation projects sponsored by the Commonwealth of Nations. The Commonwealth sponsors a variety of adaptation projects focusing primarily on building adaptive capacity among its membership and advocating climate change action globally (e.g., CCGE 2007). The Commonwealth's irregular border geometry, institutional capacity, and emphasis on national-scale assistance yield interesting discounting insights. The third case is of conflict, specifically in the hypothesized connection between climate change, forced migration, and violent conflict. Though much uncertainty exists, many believe that this causal chain could lead to significant conflict over upcoming decades and beyond (e.g., Reuveny 2007). Migration's climatic driver, the attitudes of migrant and host communities towards each other, and the functional relationship between the respective communities all yield interesting discounting insights. Collectively, these three cases show the power of the space-time discounting paradigm for analyzing climate change adaptation. The three cases are analyzed in detail below. First, however, we introduce some background on discounting.

The overarching objective of this paper is to demonstrate the importance of taking into account the propensity to discount across time *and* space in climate change adaptation. Our cases were chosen to represent a broad range of adaptation scenarios thereby indicating the broad importance of space-time discounting to adaptation. These cases, and the theory that drives them, can be readily adapted for many other adaptation cases.

2. Theory of Space-Time Discounting

Our theory of space-time discounting is an extension of the traditional time-only discounting, which is in turn embedded within the broader domain of CBA. Some background on all three topics is necessary for our discussion of discounting in climate change adaptation.

Two approaches to CBA and discounting predominate. The "descriptive" approach aims to describe how people value and discount costs and benefits, often by observing market behavior. This description is essentially an exercise in moral psychology with no inherent normative significance. In other words, the descriptions are of how people *do* make valuations, not of how people *should* make valuations. However, many analysts argue that costs and benefits should be valued and discounted based on these descriptions (Nordhaus 2007). Meanwhile, the "prescriptive" approach aims to identify how costs and benefits should be valued and discounted based on fundamental ethical principles as embodied in a *social welfare function*, i.e. a function of the welfare of the (human) members of society (Stern 2007).[2] These prescriptions need not match how people actually value and discount costs and benefits. Much debate exists over whether the prescriptions should be based on descriptions or ethical principles (Arrow et al. 1996; Baum 2009). The emphasis of this article is on descriptions of discounting. We make no claims here that these descriptions hold any prescriptive significance.

CBA, despite common perception, is not just about money.[3] It is true that most CBAs do count costs and benefits in monetary units, with many even placing monetary values on such non-market phenomena as ecosystem services and human lives (Costanza et al. 1997; Viscusi and Aldy 2003). However, classic CBA theory defines costs and benefits in terms of social welfare (Meade 1955; Drèze and Stern 1987). Here CBA can be conducted in any unit, monetary or otherwise; the unit of analysis in CBA is known as the *numéraire*. Note that different people may define social welfare differently, setting the stage for conflict, as we discuss below. While the classic theory can be extended beyond an anthropocentric notion of social welfare, in this article, the conventional social welfare approach suffices.

In this article, it is also important to distinguish between the types of value held by costs and benefits. Most CBAs neglect this, leading to analytical mistakes. Here, two types of value are relevant. Intrinsic value is that which is valuable for its own sake (Rønnow-Rasmussen and Zimmerman 2005). Throughout this article human welfare holds intrinsic value via various social welfare functions. Instrumental value is that which is valuable because it causes intrinsic value (or, more generally, causes other value; Bradley 1998). In this article several phenomena hold instrumental value, including climate, human labor, and social institutions. The distinction between intrinsic and instrumental value is central to understanding spatiotemporal discounting in climate change adaptation. For example, we might want to help someone adapt to climate change both because we place intrinsic value on her welfare (i.e. we care about her welfare for its own sake) and because we think she holds instrumental value (for example if she can help others adapt). Our examples illustrate these concepts in greater detail.

[2] A person's welfare simply means how well her life fares, which may or may not relate to how much money she has. The term welfare is often used synonymously with utility and preference. This usage is problematic: we often prefer outcomes beyond just what makes our own lives fare well. In this paper, we assume that utility and welfare are equivalent and leave open the relationship between these concepts and the concept of preference.

[3] Adler and Posner (2006) offer an excellent introduction to and extension of traditional CBA theory.

Traditional temporal discounting compares costs and benefits that occur at different times. This comparison usually uses a monetary numéraire but sometimes uses a welfare numéraire. Descriptions of monetary discounting generally involve observations of market interest rates. Descriptions of welfare discounting often use survey research (Frederick et al. 2002). Both market and survey descriptions emphasize functions in which the value of future costs and benefits decays exponentially as a function of the time delay until the cost or benefit occurs (solid curve, Figure 1). Some survey research identifies a more gradual decay, often represented by a hyperbolic function (dashed curve, Figure 1). But regardless of the specifics, all descriptions of temporal discounting use some sort of smooth decay function. Our example of the Commonwealth of Nations will demonstrate that such functions are inadequate for spatial discounting.

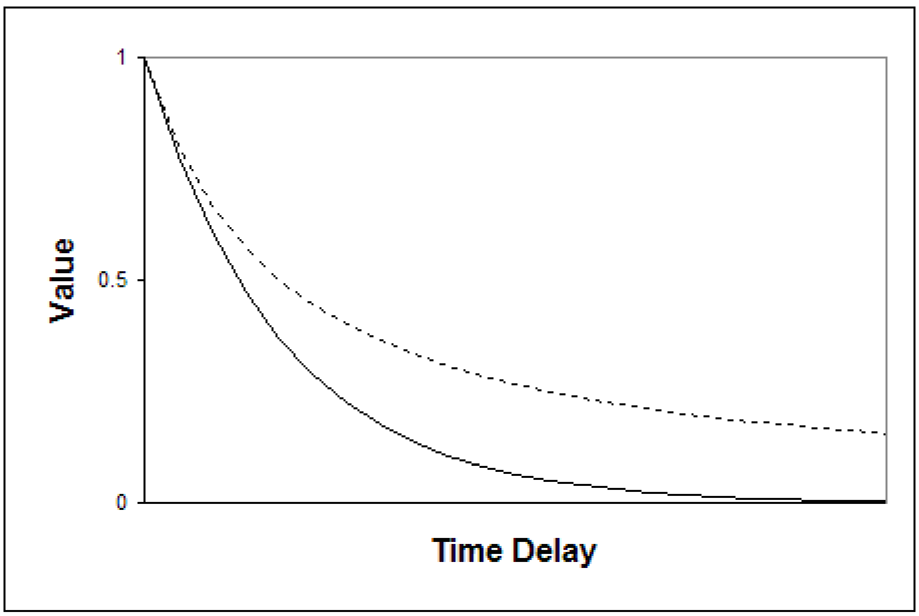

Figure 1: Exponential (solid curve: v = exp(-t)) and hyperbolic (dashed curve: v = 1/(1+t)) temporal discounting, showing the relationship between value (v) and time delay (t).

Many reasons have been given for time discounting (Cowen and Parfit 1992; Frederick 2006). Here we focus on three which are central to climate change adaptation:

1. *Welfare favoritism*. Here, future costs and benefits are considered to be worth less because individuals favor welfare that occurs sooner to welfare that occurs later. Since welfare is assumed to hold intrinsic value, to favor some welfare over others is to place more intrinsic value on some welfare than on others. The future welfare can be the individual's own welfare or it can be the welfare of one or more other individuals. Welfare favoritism across time is often labeled pure time preference (e.g. Arrow et al. 1996) because welfare at certain times is being favored purely because of when it occurs, not because of other factors.

2. *Consumption inequality*. Here, future costs and benefits are considered to be worth less because future individuals are wealthier, i.e. consume at higher rates. Consumption is an instrumental value bringing more welfare to those who consume. The underlying idea here is that a unit (e.g. a dollar) of consumption is worth more (brings more welfare) to the poor than it is to the rich. Assuming a growing economy which brings future generations greater wealth, future units of consumption will be worth less than present units of consumption. The relationship between consumption and welfare is commonly expressed in terms of the isoelastic utility function:

$$u = \frac{(c+1)^{1-\eta} - 1}{1-\eta} \tag{1}$$

Here u is utility (or welfare), c is consumption (measured in dollars or other monetary units), and η is the elasticity parameter. If η=1 then Equation 1 reduces to u=ln(c+1). Equation 1 is often written in the simpler form $u=(c^{1-\eta})/(1-\eta)$, but this form fails to cross the origin at c=0 for all η. η specifies how much more a dollar of consumption is worth to the poor than to the rich. Higher η values correspond with larger differences in the value of a dollar between the poor and rich. If η=0, then a dollar holds the same value for everyone. Empirical evidence on η is mixed: in various contexts η could be as low as 0.5 or higher than 1 (Quiggin 2008).

3. *Stimulus magnitude*. Here, future costs and benefits are considered to be worth less (or more) if they are of lower (or higher) magnitude as a stimulus of welfare. In other words, the value of some stimulus is discounted because it does not stimulate the same amount of welfare. The stimulus holds instrumental value, causing welfare for those exposed to the stimulus. For example, "a bottle of wine may taste better or worse when consumed later because of chemical reactions occurring within it, and atomic decay may reduce the radioactivity of a barrel of nuclear waste, such that a future spill would be less deadly" (Frederick 2006, p.670). In these examples, the wine and the radioactivity are the stimuli, affecting the welfare of whoever is exposed to them.

These and other reasons for discounting are almost always only considered across the temporal dimension. However, space matters for each of these reasons for discounting. People often favor the welfare of others in different places just as they favor welfare across time. For example, we might discount the welfare of people who are far away, or are part of a different family, religion, or nation. Consumption inequality exists across space as well as time. And the magnitude of a stimulus can vary across space as well as time – for example, the magnitude of the effect of radioactivity on welfare decreases as a function of distance from the radioactivity. Despite often going overlooked, this variation across space as well as time is of considerable importance to climate change adaptation and many other issues.

While temporal discounting has gotten almost all of the attention, there is some prior work on spatial discounting. One main line of work is that of geographer Bruce Hannon (see Hannon 1987, 1994, 2005; Perrings and Hannon 2001). Hannon's spatial discounting is based on the idea that individuals (human or otherwise) prefer being closer to some things (e.g., public parks or food sources) and further from other things (e.g., polluting factories or predators). Note that these costs and benefits are all instrumental values. This is spatial discounting based on stimulus magnitude. It parallels the temporal discounting in which individuals (often, but not always) prefer that instrumental benefits/costs occur sooner/later. In summary, this discounting refers to the idea that individuals have preferences for when and where instrumental values occur.

The other significant line of work on spatial discounting is in the similar concept of social discounting recently developed by psychologists Bryan Jones and Howard Rachlin (Jones and Rachlin 2006, 2009; Rachlin 2006; Rachlin and Jones 2008). Social distance here captures our sense of personal connectedness to others: family and friends are socially close to us, whereas mere acquaintances are socially distant. Assuming that these "others" exist at the same time as ourselves (i.e. we are not considering past or future friends, family, acquaintances, etc.), then this social discounting is a form of spatial discounting. In a series of experiments, Jones and Rachlin find that people generally sacrifice more consumption for the benefit of socially-close others than for socially-distant others. Since the experiments did not control for wealth, we cannot know whether the social discounting observed is due to welfare favoritism or consumption inequality, although it is likely that welfare favoritism played a dominant role unless consumption inequality happened to be strongly correlated with social distance within the experiments' sample populations. The observed sacrifice trend directly parallels the trends found in the temporal discounting literature studying current sacrifice for future benefit (see in particular Rachlin and Jones 2008). Many circumstances could be described with either spatial discounting or social discounting; throughout this paper, we use the term spatial discounting.

This theory of space-time discounting has broad applicability. One main application is in the evaluation of projects that may be undertaken by governments or other entities seeking to advance the public interest. Project evaluation is a main application of traditional CBA and time discounting theory (Dasgupta et al. 1972). The evaluation commonly involves quantifying the costs and benefits of possible projects in terms of a social welfare function, which is presumed to hold intrinsic value. The costs and benefits can be in any space-time location and can be measured with any numéraire, as long as they are aggregated so as to maximize the social welfare function. When costs and benefits are distributed across different points in space and time, then they must be discounted so that they can be aggregated per the social welfare function. This process is demonstrated in an example relevant to climate change adaptation involving crop indemnity payments.

A second application of the theory of space-time discounting is that of cooperation. Two parties tend to cooperate when they believe that cooperation will lead to mutually better outcomes than absent cooperation. However, a problem often arises when two or more parties have different views of what qualifies as a better outcome. Cooperation can thus occur under several scenarios. One scenario occurs when the cooperating parties value each others' welfare enough that they both value mutual success. This scenario involves welfare favoritism between the respective parties. Another scenario occurs when cooperation permits the enhancement of certain instrumental values, such that each party considers itself better off even if they don't place significant intrinsic value on each others' welfare. This scenario involves the stimulus magnitude of whatever instrumental values are involved. Both of these scenarios are demonstrated in an example relevant to climate change adaptation involving the Commonwealth of Nations.

A third application of the theory of space-time discounting is that of conflict. Conflict generally occurs when the parties to the conflict disagree with each other on some issue. This issue is often (though not always) an issue of space-time discounting, in the sense that the parties discount each others' welfare enough that they would rather fight than allow the other party to have its way. This scenario is typical of environmental conflicts, in which parties compete over scarce resources. Here, if the parties placed equal intrinsic value on each others' welfare, then they would agree on how to distribute the resources. Since each party would rather keep the resources for itself, conflict can arise. But other factors can also be relevant to whether conflict occurs, including how much instrumental value the parties hold for each other. These various factors are illustrated in an example relevant to climate change adaptation involving the nexus between climate change, migration, and conflict.

3. Crop Indemnity

As an example of project evaluation in climate change adaptation, we analyze indemnity payments in the agricultural sector, specifically for crops. Indemnities are payments made to a party due to a loss suffered by that party. Crop indemnities are payments made to farmers, generally due to losses suffered as a result of unfavorable growing conditions. The favorability of growing conditions are strongly dependent on climatic conditions which are expected to change significantly due to climate change (Easterling et al. 2007). Changes in the payments of indemnities are thus one expected adaptation to climate change in the agricultural sector.

In contrast with the Commonwealth of Nations and climate change-migration-conflict cases, crop indemnity is relatively conducive to quantitative CBA. This is because indemnity payment data is readily available for many jurisdictions. This data is not perfect. In particular, it is generally aggregated across broad space-time regions, instead of showing the details of each specific indemnity payment. For example, we use a data set that is aggregated across United States counties and one-year time periods. This aggregation makes the analysis more tractable but introduces important inaccuracies, as discussed below. Even with these inaccuracies, our analysis still demonstrates the importance of space-time discounting to adaptation project evaluation. Furthermore, the fact that these inaccuracies derive from the data being aggregated across space and time only makes the case for space-time discounting that much stronger.

We evaluate an indemnity payment program by estimating the increase in welfare it brings. We make no claim here that programs bringing the highest welfare increase should be chosen. While such a claim can be defensible, it would require ethical argument – namely, that all welfare holds equal intrinsic value – that is beyond the scope of this paper. Instead of making this sort of ethical argument, our interest here is in presenting and discussing the sort of analysis needed to describe welfare changes caused by indemnity payments so as to show the importance of space-time discounting to them.

Indemnity payments have distinct distributions across space and time, which imply the need for space-time discounting. The reason for this discounting is consumption inequality: payment amounts vary across space and time, as do the initial incomes of those who receive the payments. The increase in welfare due to the payments will thus depend not only on the total amount of payment but also on the distributions of initial incomes and payment amounts across space and time. By discounting the payments, the consumption inequality is factored into the analysis, bringing accurate results.

We illustrate this point using a simple example based on indemnity payments in the U.S. state of Delaware in 2007 and 2008. Delaware is chosen because it is a small state, divided into only three counties, thus making it a simple case for illustrating the importance of space-time discounting. The insights found in this simple case readily extend to more complex cases, such as for larger states or for the entire country. In general, these insights apply to any evaluation of welfare in which consumption inequality – from either initial incomes or the project under evaluation – exists across space and time.

By focusing on Delaware in 2007 and 2008, our analysis asks: What was the increase in welfare due to indemnity payments in Delaware in 2007 and 2008? Since climate change has presumably at least marginally affected agricultural conditions in Delaware in 2007 and 2008, some of these payments qualify as a climate change adaptation. They are also representative of the sorts of payments we can expect as a climate change adaptation in regions worldwide over the upcoming years. For the Delaware payments, we cannot know exactly which portion qualify as adaptation, but this uncertainty does not detract from the importance of space-time discounting to the evaluation of the overall indemnity project.

To calculate the welfare increase from indemnity payments, we approximate the welfare of a household during a time period as the natural logarithm of its monetary consumption during that period, adjusted such that zero consumption brings zero welfare (utility):

$$u(r,t) = \ln(c(r,t) + 1) \qquad (2)$$

Here, u is utility or welfare; c is consumption measured in dollars; r and t are coordinates within space and time respectively. In our calculations, we will be using household income as an approximation for consumption; we expect that this approximation does not introduce any significant inaccuracies. r can be conceptualized as an index number for households. t is always either 2007 or 2008.

Equation 2 corresponds with $\eta=1$ in Equation 1. As discussed above, some empirical evidence suggests that this may be an accurate approximation of the relationship between consumption and utility. While other functional relationships between consumption and welfare are plausible, the core result of our analysis persists as long as the relationship is such that a dollar of consumption brings more welfare to the poor than to the rich.

Given Equation 2, the increase in welfare for a household during a time period from indemnity payments is:

$$\Delta u(r,t) = \ln(c(r,t) + \Delta c(r,t) + 1) - \ln(c(r,t) + 1) \qquad (3)$$

Here, Δu and Δc are the increases in utility and consumption due to indemnity payments; the other variables are the same as in Equation 2.

The total welfare increase due to indemnity payments is then calculated by summing the welfare increases for each household at each time across the space-time region of interest, in this case Delaware during 2007 and 2008. This corresponds with a social welfare function in which all welfare holds equal intrinsic value. A fully accurate total welfare calculation would sum the income (c) and indemnity payment (Δc) for each household at each moment in time. However, such accuracy would require having and handling a very large, high-resolution data set. When data at this high resolution is unavailable, or would be too burdensome to analyze, a lower-resolution data set must be used instead. The lower-resolution data aggregates household-moments into broader clusters across space and time. This aggregation process can introduce inaccuracies if there is any consumption inequality within the clusters. In general, limitations in data and in our ability to analyze necessitate at least some clustering, as is the case here. Care must be taken to handle any inaccuracies introduced.

The data available to us is aggregated at the county scale across space and the year scale across time. This includes indemnity payment data from the Risk Management Agency of the United States Department of Agriculture (RMA 2008; 2009) and number of households and median household income data from the United States Census Bureau (2009a; 2009b; median income is used as a reasonable approximation of average income). There exists consumption inequality within counties and within years, thereby introducing some inaccuracy into our analysis. This inaccuracy further highlights the importance of space-time discounting: the less we account for consumption inequality by discounting consumption across space and time, the more inaccuracies we introduce to our analysis.

We demonstrate the importance of space-time discounting by calculating welfare increases for Delaware in 2007 and 2008 at four disaggregation configurations: no disaggregation; disaggregation across time only; disaggregation across space only; and disaggregation across space and time. The no disaggregation configuration uses values for income and indemnity payment averaged across the entire three-county, two-year period. The time-only disaggregation uses two sets of values, averaged across space within 2007 and 2008. The space-only disaggregation uses three sets of values, averaged across time within Kent, New Castle, and Sussex counties. The space-time disaggregation uses six sets of values for each of the six county-year pairs. For simplicity, we represent these aggregations and pairs using a coordinate system presented in Table 1.

Coordinate System			
	2007	2008	Aggregate
Kent	(1,1)	(1,2)	(1,Agr)
New Castle	(2,1)	(2,2)	(2,Agr)
Sussex	(3,1)	(3,2)	(3,Agr)
Aggregate	(Agr,1)	(Agr,2)	(Agr,Agr)

Table 1: Coordinate system used in the agriculture indemnity calculations.

Using this coordinate system, the total welfare increase under each disaggregation configuration can be written as follows:

No disaggregation:

$$\Delta u_{tot} = N(Agr, Agr)\Delta u_{avg}(Agr, Agr) \quad (4)$$

Time disaggregation:

$$\Delta u_{tot} = \sum_{t=1}^{2} N(Agr, t)\Delta u_{avg}(Agr, t) \quad (5)$$

Space disaggregation:

$$\Delta u_{tot} = \sum_{r=1}^{3} N(r, Agr)\Delta u_{avg}(r, Agr) \quad (6)$$

Space-time disaggregation:

$$\Delta u_{tot} = \sum_{t=1}^{2}\sum_{r=1}^{3} N(r, t)\Delta u_{avg}(r, t) \quad (7)$$

In Equations 4-7, Δu_{tot} is the total utility or welfare increase due to indemnity payments for across the entire Delaware 2007-2008 space-time region; N(r,t) and $\Delta u_{avg}(r,t)$ are the number of households and the average utility increase within the space-time region (r,t), which could be either one county-year or an aggregate across counties and/or years. $\Delta u_{avg}(r,t)$ is calculated using Equation 3 using income and indemnity payment data averaged across the region (r,t).

The number of households, income, and indemnity payment data for Equations 3-7 appear in Tables 2-4. For the number of households, aggregate values are the sum of the values within the region of aggregation; for income and indemnity payment, aggregate values are the average of the values within the region of aggregation.

Number of Households			
	2007	2008	Sum
Kent	61,641	62,889	124,530
New Castle	212,419	213,489	425,908
Sussex	114,553	116,587	231,140
Sum	388,613	392,965	781,578

Table 2: Number of households in Delaware counties in 2007 and 2008, from U.S. Census Bureau (2009a).

Median Income Per Household			
	2007	2008	Average
Kent	$47,407	$55,179	$51,293
New Castle	$59,871	$63,301	$61,586
Sussex	$50,132	$47,727	$48,930
Average	$52,470	$55,402	$53,936

Table 3: Median household income in Delaware counties in 2007 and 2008, from U.S. Census Bureau (2009b).

Average Indemnity Per Household			
	2007	2008	Average
Kent	$117.63	$106.56	$112.10
New Castle	$2.33	$11.80	$7.07
Sussex	$82.09	$49.02	$65.55
Average	$67.35	$55.79	$61.57

Table 4: Average indemnity payout in Delaware counties in 2007 and 2008, calculated using indemnity payout data from the United States Department of Agriculture Risk Management Agency (RMA 2008; 2009) and the household data in Table 2.

Table 5 shows total welfare increase within each space-time region at each aggregation scheme calculated using data from Tables 2-4. This data corresponds with the terms $N(r,t)*\Delta u_{avg}(r,t)$ in Equations 4-7. The data at each coordinate in Table 5 is acquired by plugging data from the corresponding coordinates in Tables 2-4 into Equation 3. Thus the aggregate data in Table 5 is not a function of the disaggregated county-year data in Table 5. Likewise, different portions of the Table 5 data are used for different aggregation schemes. The six county-year values [(1,1) through (3,2)] are used for the space-time disaggregation scheme. The three aggregate county values [(1,Agr) through (3,Agr)] are used for the space-only disaggregation scheme. The two aggregate year values [(Agr,1) and (Agr,2)] are used for the time-only disaggregation scheme. Finally, the one aggregate value (Agr,Agr) is used for the space-only disaggregation scheme.

Total Welfare Increase			
	2007	2008	Aggregate
Kent	152.76	121.33	271.85
New Castle	8.28	39.81	48.88
Sussex	187.42	119.68	309.46
Aggregate	498.51	395.54	891.71

Table 5: Welfare increases from indemnity payouts in each county-year and in statewide and multiyear aggregates, calculated using data from Tables 2-4.

Following Equations 4-7, we can now use the data in Table 5 to produce estimates of the total welfare increase (Δu_{tot}) for the entire Delaware 2007-2008 space-time region using each of the four disaggregation schemes. The Δu_{tot} estimates are found by summing the values in Table 5 according to Equations 4-7. These estimates are found in Table 6.

Disaggregation Scheme	Welfare Increase
None	891.71
Time Only	894.04
Space Only	630.19
Time & Space	629.27

Table 6: Total welfare increases using four different disaggregation schemes, calculated using Equations 4-7 and data from Table 5.

The total welfare increase estimates in Table 6 clearly illustrate the importance of disaggregating and discounting across space and time. Simply put, we find different results for the same parameter (Δu_{tot}) using the same data (Tables 2-4), depending on how the disaggregation is conducted. This is because the study region has consumption inequality across space and time.

It is of note that estimates of Δu_{tot} are more sensitive to disaggregation across space than to disaggregation across time. In other words, the differences between (1) no disaggregation and space disaggregation and between (2) time disaggregation and time and space disaggregation are larger than the differences between (3) no disaggregation and time disaggregation and between (4) space disaggregation and time and space disaggregation. This means that for this example, disaggregation across space is more important than disaggregation across time. This is because the consumption inequality across space affects Δu_{tot} more than the consumption inequality across time. Thus, for this example, and for similar other cases, the practice of discounting consumption across time but not across space is an ineffective approach to achieving more accurate results.

Finally, it is important to recall that the Δu_{tot} estimates in Table 6 are inaccurate because they are calculated using data averaged across all households and moments within a county-year. This averaging was performed due to limitations in the available data and because finer detail in the data was not necessary to make the core point that space-time discounting is necessary to make accurate Δu_{tot} estimates. Where further accuracy is required, further disaggregation across space and time should be conducted.

4. Commonwealth of Nations Adaptation Efforts

As an example of cooperation in adaptation, we analyze the Commonwealth of Nations. The Commonwealth is an international organization composed of nations with ties to the former British Empire. The Commonwealth includes 53 countries (Figure 2) and two billion people, cutting across geographic, socio-economic, and religious lines (Commonwealth Secretariat 2009). The Commonwealth also has a longstanding interest in climate change adaptation and mitigation, dating to its 1989 Langkawi Declaration on the Environment. The Commonwealth's ongoing climate change response activities consist primarily in meetings amongst government officials of member countries aimed at building capacity and advocating broader climate change action, often coupled with discussions of other topics as well. In 2007 alone, such meetings occurred in Belize, Guyana, Uganda, and Kenya (c.f. CCGE 2007). The Commonwealth's efforts are thus a major instance of people cooperating towards improved adaptation.

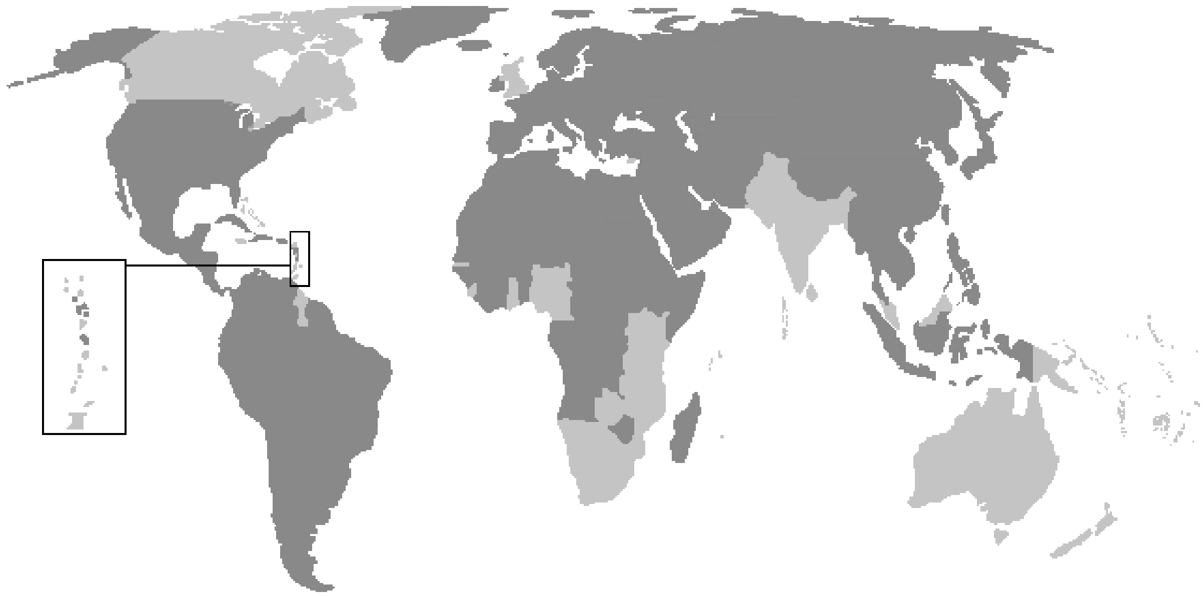

Figure 2: Commonwealth of Nations membership (light grey). Image adapted from Commonwealth Secretariat (2009, p. 2). Copyright of the Commonwealth Secretariat, reproduced with permission June 2009.

Like other adaptation efforts, those of the Commonwealth can be analyzed in a cost-benefit framework. Here, the cost is the cost of organizing and hosting meetings and producing informational and advocacy materials. The benefits are the improved adaptations of people both in the Commonwealth and beyond. The Commonwealth clearly does not strive to maximize money here, since its efforts consistently emphasize helping its poorest and most vulnerable members. Money-maximizing CBAs would instead emphasize higher-dollar adaptation projects such as protecting high-end ski resorts. However, the Commonwealth's adaptation efforts can reasonably be described as maximizing some social welfare function, since the efforts aim to improve human welfare. The specifics of this social welfare function reveal important spatial discounting insights.

We do not attempt here to conduct a quantitative analysis of how the Commonwealth discounts costs and benefits across space and time. Such an analysis would be extremely difficult given the very subtle and complex nature of the Commonwealth's efforts. Activities like advocacy and capacity building do bring benefits in terms of climate change adaptation, but these benefits are very difficult to quantify since they are spread across many stakeholders and tightly coupled with many other activities. An attempt to quantify these benefits would be so complex and fraught with uncertainty that it would distract from the simpler and more robust insights to be found from a more qualitative and heuristic analysis of how the Commonwealth discounts in its adaptation practices.

While the Commonwealth does appear, through its adaptation practices, to place intrinsic value on the welfare of all humans, it appears to place more on Commonwealth members. This is seen, for example, in its "advocacy work related to the concerns of vulnerable [to climate change impacts] member states" (CCGE 2007, p.45). In other words, the Commonwealth discounts the welfare of non-members relative to members. This discounting occurs because the Commonwealth supports global adaptation efforts but emphasizes adaptation within the Commonwealth. Such discounting is unremarkable: groups of all types tend to favor their own membership.

What is remarkable about this discounting is its irregular spatial geometry. Assume that the Commonwealth values the welfare of all people in the Commonwealth at one level and that of everyone else at another, lower level. (We will question this assumption shortly.) Then a map of the Commonwealth's welfare discounting is that of Figure 2. Notice that this map completely lacks the smooth decay of the typical temporal discounting shown in Figure 1. It is as if we favor welfare that occurs in 2010, 2012, and 2013 relative to welfare occurring in 2011, 2014, and 2015: no simple pattern exists. But while such meandering temporal discounting is unexpected and inexplicable, the corresponding spatial discounting pattern is anything but that. As noted above, the fact that the Commonwealth exhibits this pattern is unremarkable. The geometry of the Commonwealth is somewhat more interesting but its irregularity is hardly unique. We could have just as easily mapped la Francophonie, or the Christian or Muslim worlds, or many diasporas, though not all of these groups are as active on climate change as the Commonwealth. Clearly, the smooth decay functions common to temporal welfare discounting are inadequate for spatial welfare discounting.

But the fact that the Commonwealth favors its own membership in its adaptation efforts reveals more than just how it discounts welfare across space. There is another reason for this favoritism: the Commonwealth's institutional capacity. The Commonwealth's shared protocols, professional networks, and language enable it to provide more adaptation assistance to its own membership per unit cost (measured in money, effort, etc.) than to non-members. On this, it writes:

> Because member states share similar legislative and legal systems, the Commonwealth Secretariat is also well placed to facilitate networking and the review of national legislative frameworks to help ensure that these are up to date and comprehensive in their approach to sustainable development. The Commonwealth Secretariat is currently working with member states to examine legislative frameworks on environmental protection. As we have seen, this is a fundamental prerequisite to adaptation to climate change. It will also explore, through its work on human settlements, the potential for a similar programme examining legislative frameworks to support disaster risk reduction and adaptation to climate change (CCGE 2007, p.45).

In other words, the Commonwealth holds instrumental value. Thus even if the Commonwealth did not discount non-members' welfare (i.e. if it placed the same intrinsic value on everyone's welfare), it would still favor its own membership in its adaptation efforts. This fact highlights the importance of recognizing the different value types held by costs and benefits: if the Commonwealth's instrumental value was ignored, then we would overestimate how much more intrinsic value it places on the welfare of members than on the welfare of non-members.

A final point of note regarding the Commonwealth's adaptation efforts is that these efforts focus on helping its member *nations*. This is unsurprising given the Commonwealth *of Nations*' structure but is important nonetheless. This nation-favoritism means that the Commonwealth provides more adaptation assistance to small nations than to equally vulnerable small regions of large nations. For example, the Commonwealth heavily emphasizes adaptation in small island nations, which are unquestionably very vulnerable to climate change (CAG 1997). However, this emphasis comes at the expense of adaptation in regions of larger countries such as India, Pakistan, Bangladesh, and Malaysia, all of which feature regions every bit as vulnerable to climate change as the small island nations. Thus the map in Figure 2 does not accurately describe how the Commonwealth discounts welfare across space. A more accurate description would, due to the quirks of national borders, resemble a smooth decay function even less. In summary, while the Commonwealth does successfully facilitate cooperation towards adaptation, it does so in a very specific and complex way.

5. Climate Change, Migration and Conflict

As an example of conflict in climate change adaptation, we analyze conflict caused by migration that is itself a climate change adaptation. This causal chain is quite simple. Climate change will have profound effects on regions worldwide, but will have different effects on different regions. Some regions may deteriorate so much that residents adapt by migrating to other regions. Deterioration causes include sea level rise, agricultural productivity declines, disrupted water resources, and extreme weather events. The total number of expected climate refugees is highly uncertain, but some estimates have been as high as several hundred million (Nordås and Gleditsch 2007). The nub of the issue is that such migration may create or exacerbate tensions between migrant and host communities, resulting in conflict.

Several aspects of the climate change-migration-conflict nexus can be described via space-time discounting. This includes the climatic driver of mitigation, the intrinsic value that the migrant and host communities place on each others' welfare, and the instrumental value that each community offers to the other. As with the Commonwealth of Nations case, the costs and benefits involved in the climate change-migration-conflict nexus are quite difficult to quantify. Simply put, it is difficult to know the extent to which climate change causes migration, and the extent to which migration causes conflict. Any quantitative CBA of this nexus must put this uncertainty front and center or else risk arriving at very inaccurate results. However, again as with the Commonwealth of Nations case, much insight can be gained from a qualitative, heuristic analysis of the climate change-migration-conflict nexus.

The climatic driver of migration is a form of space-time discounting. Specifically, climate change causes changes over time in the instrumental value of different spatial regions. The result is that people in one region come to prefer being in a different region. In other words, they discount the instrumental value of the departure region relative to that of the arrival region. This spatial discounting is essentially variation in stimulus magnitude, comparable to Hannon's spatial discounting in that it compares spatial locations in which people can be relative to geographically-fixed instrumental values. Given this comparison, people will generally migrate when the benefit of migration (the improvement offered by the arrival region) exceeds the cost (such as transportation, psychological, and transaction costs; see Reuveny 2007, p.658). This migration then leads to conflict whenever it brings together two communities sufficiently prone to conflict with each other.

Whether or not migration induced by climate change leads to conflict is the subject of much debate. Analyses suggesting that conflict is likely generally have Malthusian tendencies (Homer-Dixon 1999; Reuveny 2007). Other analyses emphasize several competing factors which make conflict less likely (Suhrke 1997). These competing factors can be succinctly described in terms of spatial discounting of intrinsic and instrumental value.

The intrinsic value here concerns the migrant and host communities' attitudes towards each other. A key finding of the migration-conflict literature is that conflict is more likely when there are pre-existing tensions between the two communities (Reuveny 2007). Here climate change is only one of multiple conflict causes. For example, intra-national migration may cause less conflict than international conflict so long as compatriots tend to like each other more. In other words, the more the two communities favor, or discount each others' welfare, the more likely it is that conflict will result. If the communities happen to place the same intrinsic value on each others' welfare (or, more generally, if the communities happen to support the same social welfare function), then conflict will in general not occur. This connection between spatial discounting and conflict was first described by Hannon (1987). It is of clear relevance to conflict in the climate change context, whether due to migration or other factors such as induced resource scarcity.

But the spatial discounting of welfare alone is insufficient to cause conflict. Communities could discount each others' welfare but avoid conflict if the communities hold instrumental value for each other. For example, migrants often provide (instrumentally) valued labor for the host community, which then provides money, civic infrastructure, and other services in return (Suhrke 1997). If this instrumental value is high enough, it may outweigh other factors, thereby preventing conflict. This instrumental value adds an additional form of spatial discounting: people prefer being near other people who can help them. As with the spatial discounting of regions discussed above, this spatial discounting of people is grounded in changes in instrumental value across space. Thus Hannon's instrumental value-based spatial discounting is broadly applicable to the climate change-migration-conflict nexus.

6. Conclusion

As the cases of crop indemnity payments, the Commonwealth of Nations, and the climate change-migration-conflict nexus illustrate, climate change adaptation, like many nature-society phenomena, features rich complexity that poses significant analytical challenges. This complexity has hindered past climate change adaptation CBA research, contributing to the dearth of adaptation-focused CBA studies. In this article, we apply a new approach to space-time discounting to climate change adaptation which better handles the complexity, thereby facilitating climate change adaptation CBAs.

The crop indemnity payments case illustrates the importance of space-time discounting in the evaluation of adaptation projects. The uneven distribution of household incomes and indemnity payments across space and time necessitates space-time discounting: if payments are not discounting across space and time, then inaccurate results are obtained. This point is seen clearly in the simple case of payments in the three counties of Delaware, United States during 2007 and 2008. The core insights from this case, as well as the methods used to produce these insights, readily extend to more complex cases, including other climate change adaptation projects involving costs and benefits that are distributed across space and time.

The Commonwealth of Nations illustrates the importance of space-time discounting in cooperative adaptation efforts. The Commonwealth's irregular border geometry shows that the smooth decay functions common in temporal discounting are inadequate for spatial discounting. The Commonwealth's institutional capacity shows that an organization's instrumental value must be recognized to avoid misinterpreting the relationship between its actions and what it places intrinsic value on. Lastly, the Commonwealth's national scale of operation shows how geopolitical circumstance can further distort descriptions of spatial discounting.

The climate change-migration-conflict nexus illustrates the importance of space-time discounting in conflictive adaptation efforts. The climatic driver of the migration shows that changes in how people spatially discount the instrumental value of different locations can cause the people to migrate across these locations. The attitudes of migrant and host communities towards each other show how conflict can occur when the communities discount each others' welfare. Lastly, the functional relationship between the respective communities show that even when the communities discount each others' welfare, conflict might not occur if the communities provide instrumentally valuable assistance to each other.

In closing, we emphasize that our analysis in this article is purely descriptive and without any attention to prescription. However, the analysis can readily be extended for prescriptive purposes. Doing so requires some choice of intrinsic value to evaluate the prescription according to. The choice in turn requires taking certain ethical positions. Thus the spatiotemporal discounting theory presented here is applicable to both descriptive and prescriptive analysis, for climate change adaptation as well as other topics. Moreover, our analysis strongly indicates that the analytical methods of CBA must include space in addition to time in the calculus of discounting.

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