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Valuing Uncertainty Part II: The Impact of Risk Charges in Dealing with Time Issues in Lifecycle Analysis and GHG Accounting

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Abstract

We have greater certainty for what has happened in the past than for what will happen in the future. Uncertainty on the impact and value of emissions can be very large. Given all of the elements of uncertainty, we are challenged to set global targets for limiting the environmental impact of emissions, to distribute those targets among the many parties responsible for emissions, to evaluate the trajectories toward targets, to understand the risk involved in not meeting targets, to motivate the collective efforts and burden sharing or trading, and to verify that targets have been achieved. We need a clear and consistent framework for dealing with uncertainty and in this article we use the notion of a risk charge on uncertainty to investigate issues of time in GHG and lifecycle analysis accounting. Results: We address critical issues of short-term storage, time horizons, permanence, trading agreements and model error, and explain the consequences of a risk charge on the associated uncertainties. Conclusions: We demonstrate here how the framework we have built naturally extends to address most types of issues that might arise in placing a value on the uncertainty of GHG emissions, and in quantifying management trade-offs and policy strategies for mitigation and adaptation of climate change.

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Introduction

In Marland *et al.*, a case was made for using a **risk charge** as a means to address **uncertainty** in GHG accounting [1]. For standard calculations, the risk charge is a straightforward consequence of the standard uncertainty calculations related to emissions estimates. The risk charge is added to or subtracted from the base value of the emissions or sequestration to create a conservative bound for the effects of the uncertainty. That is, we assume that the value of emissions is increased in proportion to the magnitude of the uncertainty, while the value of sequestrations or offsets is decreased in proportion to the magnitude of their uncertainty. This valuation of uncertainty admits the risk involved in our accounting methods and encourages reductions in uncertainty.

Dealing with uncertainties over time presents a more formidable task. The basic question posed here is whether the value of GHG emissions varies with the time of emissions – do emissions now have the same value as emissions some time in the future? In this article we address some of the time issues in GHG and **lifecycle analysis** (LCA) accounting in the context of a risk charge designed to deal with uncertainties. For this purpose we draw on ideas and methods from actuarial science to motivate and guide our calculations. This same approach has been used in Shirley *et al.* to motivate different possibilities for contract structures and to calculate contract values [2]. In this article, we utilize this approach to address various time issues.

We can consider that there are two primary categories of error or uncertainty in carbon accounting:

- How much carbon is released (or sequestered);
- When (and possibly where) the carbon is released (or sequestered).

Issues of time sensitivity have been gaining more emphasis in discussions recently (e.g., Marland and Schlamadinger [3]), and there are different camps that propose a variety of approaches for dealing with the temporal distribution of carbon sources and sinks.

Key terms

Risk charge: Term derived from the insurance industry describing a fee added to the basic cost of a good or service that incorporates potential costs incurred to the seller as a consequence of the sale. An example is that of selling automobile insurance and adding a charge that reflects the probability of an unexpected number of accidents involving policy holders occurring at the same time.

Uncertainty: Value that defines the accuracy level of a reported value. This can be due to measurement error, lack of available data, modeling assumptions or future estimation.

Lifecycle analysis: Analysis of a product through its whole lifetime. In the case of a carbon-containing product, many people consider the lifecycle to run from atmosphere to atmosphere or from raw material extraction to disposal (cradle to grave). Where exactly to start and end the cycle is not completely standardized, but the purpose is consistent.

Time horizon: Time beyond which events are not considered to be relevant. In the case of GHG emissions accounting, a time horizon might assume that emissions from a particular process taking place 100 years out are small enough to be negligible or possibly that after 100 years we will have a whole new set of climate issues facing us, making the current accounting irrelevant.

These range from using a discount factor on carbon flows [4,5], to deriving a time-dependent damage function [6–10], and trying to establish the social cost of emissions [11,12]. A recent advisory group to the California Air Resources Board struggled without reaching consensus but did provide the consensus statement that *"the timing of emissions are important and, as a general goal, policy should differentiate based on timing where possible"* [13].

With our proposed handling of uncertainty, there are important impacts on some of the key issues surrounding the handling of time in GHG and LCA accounting. In this next section we show the effect of accurately describing the timing of emissions when emissions have value. Because of natural and practical limitations with anticipating the future over extended time frames, the level of uncertainty moving forward in time is frequently quite high. Using the idea of a risk charge as a means to make conservative estimates provides a consistent way to deal with these sensitive time issues. To minimize the large uncertainties associated with long-time projections, we are motivated to find ways to minimize the role of long times in our estimates, agreements and projections.

Discounting & present values

With a cost associated with emissions of carbon, we are forced to confront the issue of timing because emissions this year may not have the same value as emissions or sequestrations in subsequent years. The importance of the time value of carbon has been recognized for many years (i.e., Richards [14]) but never with sufficient consensus to enter national or international agreements or LCA or GHG accounting generally.

The time value of carbon emissions is of particular concern in considerations of land-use change and biofuels where emissions and sequestration occur within the same system but not necessarily contemporaneously. Time is equally relevant for any harvested wood products where there will be a time lapse between production and oxidation of the product and for lifecycle analyses generally, where emissions and sequestration cover the interval from production to end-of-life management. For example, while biofuels are typically used in the same year that they are produced, the corresponding sequestration that balances the emissions over the same space may take multiple years, depending on the fuel. Looking at longer-lived products, both emissions and sequestrations may occur over the balance of many years. It makes sense that a party should not receive credit for a sequestration until it happens and it makes sense that a payment for emissions should not be required until it happens.

Issues of time enter the discussion of biologic carbon flows in several ways as:

- Carbon flows from an initiating process may be distributed over time (e.g., over the lifetime of durable wood products);
- Carbon flows within a system can go both directions but not necessarily simultaneously (e.g., biofuel production and consumption);
- Human intervention changes the rate of carbon flows (e.g., harvest of forest resides for energy accelerates the return of carbon from biospheric stocks to the atmosphere).

In the first case, we have shown previously that for long-lived, carbon-containing products the value of emissions differs dramatically when the lifetime of products is represented as accurately as possible [15]. The decay of the product can be described using a probability distribution for the particular product or class of products:

$$\frac{ds}{dt} = J(t) - \int_0^t J(t-\tau)P(\tau)d\tau$$

where s is the stock of the product, J(t) is the production term and P(τ) is the probability distribution representing the product's likelihood of decay. The integration variable for the time since production is τ. The integral sums the removal from the stock of all the previous years' productions according to the proportion that is expected to decay in each year following production. Probability distributions can be selected for use based on how appropriately they reflect the particular product stock being considered. In Marland *et al.*, a model using the Γ-distribution was developed that considers the year of maximum decay and the year of 95% decay for various forest products [15].

We use the representation of forest products to illustrate the issues, their importance and the role of uncertainty, when dealing with emissions (or sequestration) over time and when emissions have value. The point is that if we can describe the probability distribution of emissions over time, and if we can estimate a discount rate, then the net present value of emissions can be calculated and uncertainty dealt with as a function of the time profile.

The distributional approach provides a template for modeling the probability of oxidation of carbon. For practical reasons, some other distributions may sometimes prove more useful in accounting than the Γ-distribution illustrated in Figure 1. Due to the potential difficulties that may be faced when implementing contracts and policies based on a probability distribution with an infinite tail, a motivation for an alternate distribution, using a more practical time frame that has a finite end point arises. We introduce two potential finite distributions: the β-distribution and the Γ-distribution with a truncated tail. We use 100 years as our time frame for determining the present value of the carbon emitted. The use of a 100-year time horizon in which all carbon emissions are to be paid for was selected due to its recent use in the literature (among many, e.g., [16–18]). Note that the following text refers to wood products but these should be interpreted to represent any products that contain real or embodied carbon; including forest trees, geologic reservoirs or products that will result in carbon emissions during end-of-life processing.

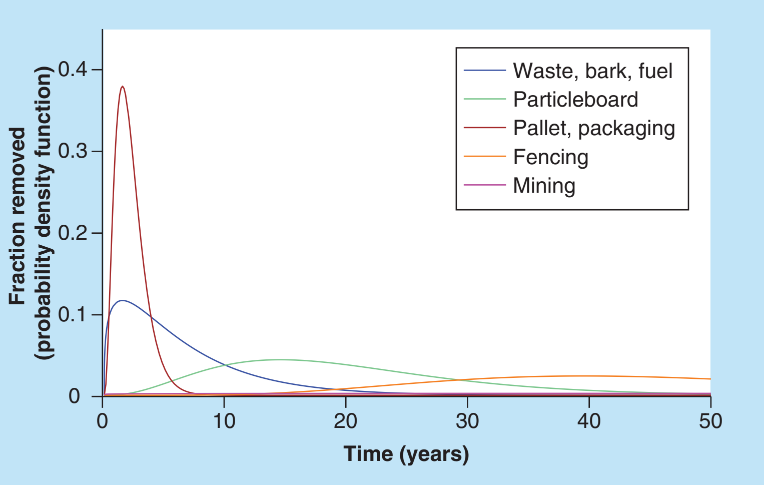

Figure 1. The release of carbon from durable wood products follows a probability density curve that depends on the use of the product and the expected lifetime. The year of peak decay for long-lived products varies. Data are for five of the wood product classes described in Table 1.
Adapted with permission from [15] © Springer (2010).

Time horizons & permanence

To facilitate our discussion of time horizons, we briefly review the calculations for the present value of emissions distributed over time. The present value of the cost per unit of emitted CO_2 in year T is $b_T e^{-\gamma T}$ where b_T is the price of carbon emissions at time T and γ is the discount rate. Assuming an initial price b in the price of carbon and a level annual rate of increase r in the price of carbon, $b_T = be^{rT}$. The expected present value of the cost of 1 unit of emitted CO_2 is then given by:

$$\overline{C} = E[b_T e^{-\gamma T}] = E[be^{(r-\gamma)T}] = \int_0^\infty be^{-(\gamma-r)t} P(t)dt$$

where P(t) is the probability distribution for the likelihood of decay as previously described. The resulting aggregate (inflation adjusted) discount rate is then given by $\delta = \gamma - r$.

A time horizon is a period of time within which all relevant processes occur. Or in other words, a time horizon assumes that beyond a certain time, nothing relevant to the calculations takes place.

Although general agreement on the relevant time is not universal, we use 100 years in our model. The primary concern that a time horizon creates seems at first to be a housekeeping detail. Assuming that some finite amount of carbon contained in a product not oxidized after 100 years is going to be oxidized eventually, we ask the question of how to account for that quantity. If we assume that the quantity is small, which it is for many products, we still need a standard method for dealing with it. For very small quantities, it does not matter a great deal how it is handled, but it is important to handle it consistently. The bigger consideration is what to do about very long-lived carbon-containing products. A large fraction of some carbon-containing products may outlast the 100-year horizon, and it is important to know how to deal with those emissions and to be consistent in methodology across all emission processes. In many cases, the standard procedure has been to assume that the carbon contained in these products is permanently sequestered and is never released to the atmosphere.

In order to address this issue, we look first at two alternate probability distributions that describe the lifetime of a carbon-containing product. These alternate distributions exemplify two different approaches to dealing with the 100-year time horizon. The specific distribution chosen in practice likely depends on the particular product and process in question.

β-distributions

The Γ-distribution is a distribution over an infinite time domain that reflects the idea that emissions from a product may occur at any point in the future. If we are restricting our considerations of carbon emissions to 100 years by implementation of a time horizon, using an infinite time domain may not be the best choice. The β-distribution shares similarities with the Γ-distribution but is inherently finite; that is, it is only nonzero on a finite interval. The two parameters, α and β, can also (such as the two parameters that describe a Γ-distribution) be determined based on the year of maximum decay and the 95% decay period for each specific product. If δ is the aggregate effective discount rate and t is the time period over which we are concerned, then the following expression for $\overline{C}$ represents the expected present value of 1 ton of emitted carbon distributed over 100 years, discounted over 100 years, and assumed to cost US$50 per ton.

$$\overline{C} = 50\int_0^{100} e^{-\delta t} P_\beta(t)\,dt$$

where:

$$P_\beta(t) = \frac{t^{\alpha-1}(100-t)^{\beta-1}}{B(\alpha,\beta)100^{\alpha+\beta-1}}$$

is the probability density function for the β-distribution with support $0 \leq t \leq 100$ and B(α,β) is the β-function. Although we were able to obtain values for short-term products, one of the limitations to the β-distribution is its inability to compute the present value of products whose 95% decay period is beyond the scope of the present value calculation (100 years). To use a β-distribution, we would need data on early portions of the decay distribution in order to make the fit. Therefore, the data in **Table 1** and the probability distribution curves in **Figure 2**, which shows a comparison between the two distributions, only include products whose 95% decay period is within the 100 year time frame. The choice of the decay distribution can create subtle differences. It is difficult to distinguish between distributions fit to the same data.

Truncated Γ-distribution

Due to the limitations found in using the β-distribution for CO_2 emissions from extremely long-lived products (not having appropriate data to fit the parameters), a truncated Γ-distribution provides another approach. This distribution uses the same parameters, k and θ, as the full Γ-distribution. However, the entire present value is calculated within a finite time horizon, which we again assume is 100 years. The expected present value, $\overline{C}$, of 1 ton of carbon emitted, but distributed over time, at an assumed cost of $50 per ton is as follows:

Table 1. Comparison of present values for CO_2 emissions cost using a best fit for different distributions and a 5% discount rate.

Product	Mean life (years)	Gamma (full; US$)	Gamma (truncated; $)	Beta ($)
Waste, bark, fuel	6.42	37.53	37.53	36.64
Pulpwood	1.70	46.05	46.05	45.17
Particleboard	19.92	20.71	20.71	20.57
Pallet, packaging	2.18	44.91	44.91	46.79
Fencing	46.47	6.81	6.81	8.89
Construction	175.54	0.18	0.44	NA
Mining	348.10	2.13	2.37	NA

Construction and mining data do not allow a fit for the β-distribution since some of the fit data lie outside the 100 year domain. We assume a cost of $50 per ton carbon emitted.
Data taken from [27].

$$\overline{C} = 50\int_0^{100} e^{-\delta t} P_\Gamma(t)\,dt + 50e^{-100\delta}\int_{100}^{\infty} e^{-\delta t} P_\Gamma(t)\,dt$$

where:

$$P_\Gamma(t) = \frac{1}{\theta^k\Gamma(k)}t^{k-1}e^{-t/\theta}$$

is the probability density function for the Γ-distribution Γ(*k*,θ) and Γ(*k*) is the Γ-function. Here, we discount all emissions that might occur after the 100-year horizon by 100 years and assume that all of those emissions happen at that time.

Notice what we have effectively done with the idea of the truncated Γ-distribution. We have cut the Γ-function short, stopping at 100 years, and then added on an additional cost to compensate for the emissions that occur after that horizon. This is exactly analogous to adding a risk charge for the error or uncertainty in making the assumption that emissions that occur after the 100-year mark can be considered permanent. The truncated Γ-function has no impact (at three significant figures) on products with mean lifetimes and product oxidation that are nearly completed within 100 years. Note that because the β-function is less peaked in the fits of the data, it has yielded lower values for the present value of very-short lived products.

Permanence

Some strategies have been proposed to 'permanently' sequester carbon [19]. While some of these ideas have clear merit, the concept of 'permanent' means different things to different people. With any strategy for carbon sequestration there will always exist risks of loss or leakage. Rather than assume that these strategies are 'permanent' without further consideration, we suggest that a risk charge be assessed to reflect the probability of success of the sequestration (or pessimistically, of release). This might consist of assuming a 100-year storage to produce a discounted emissions cost, or something similar that varies with a careful examination of the risks and probabilities.

In considering both carbon release over extended periods and the prospect of permanent sequestration, we suggest that the idea of a risk charge can include both the difficult issues of uncertainty and error and the projections of sequestrations and emissions in time.

A distributional approach to risk charge

In Shirley *et al.*, a table was developed showing the effects of a mis-parameterization of the oxidation distribution on the cost of carbon, as well as the effects of differing discount rates [2]. This sensitivity analysis represents a precursor to understanding the uncertainty in calculating the cost of carbon emissions or sequestration in long-lived products. In this section, we

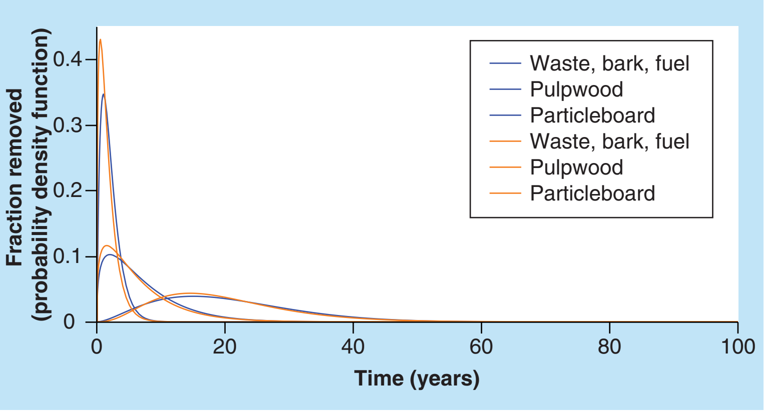

Figure 2. A comparison with the β-distribution (orange) and the γ-distribution (blue). Data illustrated are for the wood products shown in Table 1 with mean lifetimes less than 100 years.

extend the previous sensitivity analysis to an approach for calculating a risk charge in long duration products.

To understand our approach, we first construct an analogy from the actuarial theory of life insurance. Consider a group of insured persons all of whom are the same age (newborns) subject to the same mortality and possessing \$50 of life insurance. If each life is viewed as independent, then the variance or SD from the expected present value of the cost using the future lifetime distribution represents the uncertainty in the expected cost of insuring the group. In the case of independent lives, the uncertainty measured as the SD divided by the expected value is a decreasing function of the number of insureds; that is, the confidence interval for the mean cost becomes narrower as the number of insureds becomes larger.

This measure of uncertainty seems unlikely to have value in our case. For the oxidation distribution that is used to calculate the proportion of carbon in the material oxidized at a particular time in the future, it is difficult to define individual independent units of material in the same manner in which we define independent insured lives in the group insurance model. However, we can draw on another tool used by actuaries to assess uncertainty. In the group life insurance example, even after a mortality table is chosen for a particular group of insureds, a factor can be applied to each rate in the table to reflect the specific risk characteristics of the group or, more to the point in our case, as a provision for risk of adverse deviation (provision for adverse deviation; PAD) from the expected [20]. By analogy, we wish to capture uncertainty in the amount and timing of oxidation by applying a PAD (multiple) to the oxidation distribution.

To demonstrate the calculation and the effect of a PAD in the group insurance example, Table 2 presents a partial hypothetical mortality table for a newborn. Hence, the best estimate probability that a newborn who survives to age 1 dies in the second year is 0.01. Notice, in this example, the mortality rates with PADs are obtained by applying the factor 1.5 to the best estimate mortality rates in the second column representing a 50% increase in the mortality rate at each age. Calculating the expected present value of claim payments for \$50 of life insurance for the first 2 years (2-year term) using the best estimate mortality rates we obtain:

$$50 \cdot 0.05 \cdot e^{-0.05} + 50 \cdot 0.95 \cdot .01 \cdot e^{-0.1} = \$2.81$$

Recalculating using mortality rates with PADs:

$$50 \cdot 0.075 \cdot e^{-0.05} + 50 \cdot 0.925 \cdot .015 \cdot e^{-0.1} = \$4.19$$

The resulting charge for uncertainty using the PAD is (4.19 - 2.81) = 1.38, which is less than the 50% of the original expected present value.

In the context of carbon emissions and sequestration, the mortality rate becomes the rate of oxidation and the entries in the mortality (oxidation) table represent the proportion of material oxidized from time t to time t + 1. However, since an oxidation table is discrete in nature, and our model is continuous in nature, a continuous counterpart is needed for the oxidation rate in order to apply a PAD. In the continuous case, the oxidation rate at time t is approximated by the force of oxidation defined as:

$$\mu(t) = P(t)\left(\int_t^{\infty} P(\tau)d\tau\right)^{-1}$$

where P(t) is the oxidation distribution. The force of oxidation times a small time increment, μ(t) dt, represents the expected proportion of the remaining material that will oxidize in the time interval (t,t+dt). After the force of oxidation is determined, the expected present value of the cost of the carbon emission $\overline{C}$ is calculated before and after the factor is applied to μ(t) to determine the PAD associated with the increased oxidation rate. To calculate $\overline{C}$ after the PAD is applied, the modified oxidation distribution is constructed as follows. If k is the factor applied to the force of oxidation, we obtain the modified force kμ(t). From this force of oxidation the resulting survival distribution is $S(t) = \exp\left(-\int_0^t k\mu(\tau)d\tau\right)$ [21], which yields the modified oxidation distribution $P_{mod}(t) = k\mu(t)S(t)$. Therefore $\overline{C}$ after the PAD is given by:

$$\overline{C} = 50\int_0^{\infty} e^{-\delta t} P_{mod}(t)dt$$

Table 2. A simple example for a provision for risk of adverse deviation in life insurance with mortality increased by 50% for each age class.

Age	Mortality rate (best estimate)	Mortality rate (with provision for risk of adverse deviation)
0	0.05	0.075
1	0.01	0.015

The analysis shows that the resulting risk charge of US\$1.38 is 49.11%, of the original \$2.81 rather than the 50% that intuition might suggest.

Key terms

Discounting: Since money can be invested, money now is considered more valuable than money in the future. In addition, an object that has a value now may be worth more or less in the future, depending on how its value changes with respect to how the value of money changes. In the context of carbon emissions, we might consider that emissions now are more costly than emissions in the future. Typical assumptions range between 0 and 7% discounting per year.

Permanence: Used in reference to an action plan that is assumed to have perpetual implications. In climate change some consider pumping CO_2 into the ground as being a permanent sequestration, since it is presumed to stay there in perpetuity. Others might disagree.

In Table 3, we demonstrate this PAD for various factors applied to the oxidation rate as well as varying the parameters in the oxidation model showing the effects of misparameterization. The summary results use the full Γ-distribution for the three different products illustrated. By changing values for k and θ by combinations of ±5% and to each case applying an increase to the force in oxidation of 5, 10, 15 and 20%, we record the maximum downside effect.

Therefore, if the risk charge for waste/bark/fuel includes a provision for a 15% higher oxidation rate than that currently expected and modeled, as well as the possibility that the parameters in the model may vary by ±5% of the parameters previously determined, then the risk charge per ton of carbon emission would be $2.11 or 5.6% of the expected present value of cost, $37.53. Notice from the table that this risk charge is higher in relative terms with the increase in product duration. This is due to the impact of the uncertainty measured over a longer period of time.

Trading time for space

Because forecasting forward in time contains significant uncertainty, there is a strong benefit in using accounting methods that use shorter periods of time to calculate present values. One idea for decreasing the time we look forward is to trade time for space. The more that multiple emissions and sequestrations can be matched up over a short period of time, the less the longer time uncertainty plays a role. Hypothetically, a life insurance company may accomplish this same objective by having a large number of similar policies with a relatively stable age distribution over time for insureds of a similar risk class, rather than anticipating the time dependent outcomes for individuals. If priced according to actuarial principles, in this case net premium income each year should, on average, offset claims paid in that year. This is basically an argument using the law of large numbers. The larger the numbers, the closer the sample mean lies to the expected value.

Suppose we compare two forests. One is a single 60 ha forest (a forest stand) that is cut down and regrown over 60 years, the other is a 60 ha forest

Table 3. The effect of increased oxidation pressure on the system.

Oxidation factor (%)	Present value (US$)		Risk charge ($)		Percentage of expected present value of costs (first column)	
	0%†	5%†	0%†	5%†	0%†	5%†
Waste, bark and fuel (mean life 6.42 years)						
0	37.53	38.55	0.00	1.01	0.0	2.7
5	37.93	38.94	0.40	1.40	1.1	3.7
10	38.32	39.30	0.78	1.76	2.1	4.7
15	38.67	39.64	1.13	2.11	3.0	5.6
20	39.00	39.95	1.46	2.42	3.9	6.4
Particleboard (mean life 19.92 years)						
0	20.71	22.47	0.00	1.75	0.0	8.5
5	21.08	22.86	0.37	2.15	1.8	10.4
10	21.44	23.22	0.73	2.51	3.5	12.1
15	21.78	23.57	1.07	2.86	5.2	13.8
20	22.11	23.89	1.39	3.18	6.7	15.3
Fencing (mean life 46.67 years)						
0	6.81	8.17	0.00	1.36	0.0	19.9
5	7.00	8.38	0.18	1.57	2.7	23.0
10	7.17	8.58	0.36	1.77	5.3	26.0
15	7.35	8.78	0.53	1.97	7.8	28.9
20	7.51	8.96	0.70	2.15	10.2	31.6

The oxidation factor is an increase in the pressure of oxidation separate from the specific of the parameters in the model. This provides a consistent way of dealing with risk charges that is independent of the details of the parameterization of the model. Note that the risk charge is a noticeably smaller percentage than the corresponding oxidation factors.

†Parameter errors.

(normal forest) shown in **Figure 3** that has 1 ha cut each year while the other 59 continue to grow to compensate in sequestration for the one that was cut. While there may be some debate over the equality of these two scenarios, the resolution falls to a single driving issue, **discounting**. Discounting creates an imbalance in the two because the sequestration of carbon into the two forests takes place at different times. With no discounting, the two situations really would be equivalent. If 60 single hectare forests were combined in a way that staggered their harvest, then they would act in a conglomerate as if they were a single 60 ha normal forest.

The accounting for the larger forest is easier because we don't have to deal with time. Since discounting creates a differential between the two forests, the estimation of the discount rate becomes vitally important to the comparison. With the 60 individual forests, if each is viewed in isolation, time and discounting play an important role. However, if we can deal with a single larger forest for a single year, we don't have to make projections and can compensate for the emissions with concurrent sequestration in the same year. With the larger numbers, the balancing between emission and sequestration can be done each year rather than over time. Uncertainty for future years is still large, but that future uncertainty no longer affects current uncertainty.

The result is that the uncertainty in economic forecasting is kept in the future by averaging in space and by keeping the accounting periods as short as possible.

Agreement contract lengths

In Shirley *et al.* an analogous relationship between the cost of life insurance and the cost of emitting carbon from long-lived products was developed [2]. Comparing these two seemingly different fields led to surprising similarities and new methods for valuation of oxidized carbon, payment plans for this oxidation, contract possibilities and an approach to understanding the implications of continued production of carbon-containing products.

For very long-lived, carbon-containing products, the time it takes for most of the carbon to be oxidized can be beyond the typical term of a contract. It could take 1000 years, for example, for forest products used in mining applications to oxidize 95% of the carbon contained in them. The uncertainty of contracts for time horizons extended far into the future is much greater than for shorter-term contracts, causing longer term contracts to have a high risk charge. At the same time, for very long-term commitments, it is difficult to imagine the continuity of the involved parties.

In order to facilitate contracts for products or services that involve decades to centuries to release or re-capture most of their carbon, different options for contract length must be available. Short-term contracts that can be renewed after an n-year term can help address the problem associated with the higher risk charge. The length of these contracts can provide a much more manageable risk charge, especially for early carbon markets that may have insufficient data and costs that are still being defined. The rules developed under the UNFCCC for dealing with afforestation and reforestation under the clean development mechanism provide an example where this kind of focus on shorter term commitments has been implemented for carbon sequestration where **permanence** is not assured [22].

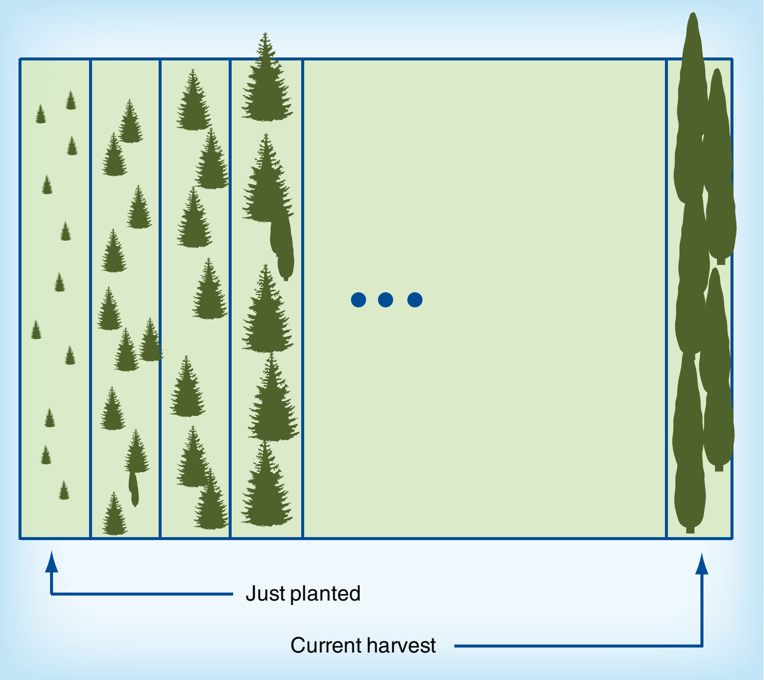

Figure 3. In a normal forest, trees are harvested after 'n' years. This means that a fraction of the forest (1/n) is harvested each year. In an idealized year, the amount of carbon removed from the forest in the harvest is the same as the amount sequestered in the nonharvested portion.

The value of short-term storage

Finally, we look at one of the contentious debates surrounding carbon sequestration, the value of short-term storage or delayed release of CO_2. Some argue that short-term storage has no value (e.g., Kirschbaum [23]) while others find sources of value in temporary storage (e.g., Dornburg and Marland [24]). Others have suggested approaches to define an equivalence between permanent and temporary carbon storage (e.g., Fearnside *et al.* and Kim *et al.* [25,26]).

We have argued that the costs of carbon emissions should be due upon the actual release of the carbon. This means that a careful account of when that carbon

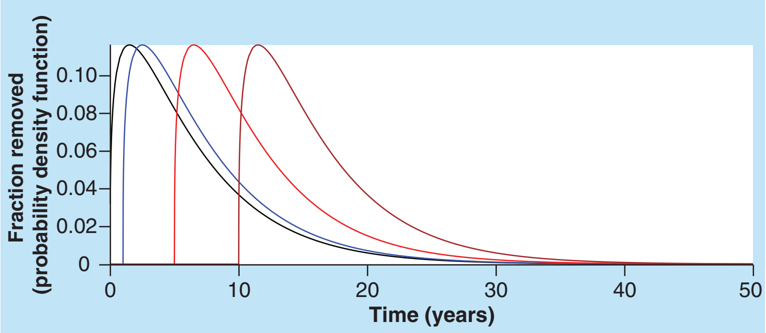

Figure 4. To calculate the simple effects of short-term storage, the distribution for the rate of release of CO_2 can be shifted over a set number of years. A present value calculation of the emissions then provides a means to compare the different lengths of storage as seen in Table 2. This figure shows the release of CO_2 from waste, bark and fuel, and when the start of decay is delayed by 1, 5 and 10 years.

is released from various carbon-containing products or practices is economically important. This economic value is, of course, only partially linked to the environmental value, as discussed elsewhere [23].

The cost of carbon emissions is calculated here as a present value calculation of the probability density with a discounting factor that takes into account both economic growth, carbon price changes and risk adjustments.

In the cost calculations of Marland *et al.*, the present value of the release of CO_2 is calculated for different categories of durable wood products [15]. The calculations also reveal the potential for additional calculations on payment strategies and contract structures [2]. In addition, the tangible benefits of short-term storage are accessible as well.

Table 4. Present value calculations for different product streams and delays†.

Usage	Distribution parameters k, θ	Storage time (years)	Cost per ton (US$)
Waste, bark, fuel	1.305, 4.918	0	41.78
	Mean lifetime	1	40.55
	6.42 years	5	35.96
		10	30.95
Particleboard	3.676, 5.419	0	28.74
	Mean lifetime	1	27.89
	19.92 years	5	24.74
		10	21.29
Construction	6.740, 25.045	0	1.14
	Mean lifetime	1	1.11
	168.80 years	5	0.99
		10	0.85

Costs are calculated based on a 3% inflation adjusted discount rate as discussed in the section titled 'Discounting & present values' and $50 per ton of CO_2. The percentage saved by storage in each product is the same even though the total absolute differences are different. A larger factor may be if short-term storage results in a change in the use of the product after storage. Shifting from one product category to another might create large savings or large expenses.
†See Table 1.

Assuming, for the sake of illustration, that a short-term storage strategy eliminates all carbon decay for the period of the storage, we can assume that the carbon release after storage follows the same time course as it would have, but with a delay until the beginning of that release (Figure 4). Mathematically, this corresponds to multiplying the probability distribution by a Heaviside function and applying a shift. The results of delaying the release are illustrated in Table 4.

Here we assume a cost of $50 per ton of CO_2 released with 3% discounting (incorporating changes in both basic economics and carbon cost). The parameters k and θ are the parameters of the Γ-probability distribution that reflect the expected time course of the release of the carbon from that product. These parameters are based on the parameters used by Marland *et al.* [15].

This means that there is value in short-term storage and that the absolute value in short-term storage of carbon destined for use in short-term products is more than the absolute value in short-term storage of longer-lived products. This result is supported by previous papers that suggest that although short-term projects are not as valuable as long-term projects, changes or improvements to short-term projects have a larger absolute effect than changes or improvements to long-term projects [27,28].

What is less apparent in this table is the potential for opportunistic benefits. If carbon that would have been used for a short-lived product is stored for some time and then shifted to a product with a longer expected lifetime, the cost savings could be much larger. For example, suppose that wood harvested for fuel is stored for 5 years, and then targeted for use as chipboard in construction. The original present value was $41.78 per ton CO_2 emitted and the resulting present value is $0.99 per ton. This constitutes a saving of $40.79 per ton. Of course, this works in the other direction as well. If a carbon-containing product is stored only to be used in a product with a much shorter lifetime, this scenario can result in a loss rather than a gain. Wood designated for construction that is saved for 5 years, but then used for fuel, shifts a present value of $1.14 per ton of CO_2 to $35.96, for a loss of $34.82 per ton.

The conclusion is that short-term storage does have financial value and that this value depends heavily on the use of the product. Products with shorter expected lifetimes benefit more from storage than products with longer lifetimes. We also find that changes in product flow can drastically change the value, for good or bad. But, most importantly here, there is great benefit in reducing uncertainty by accurately describing the time path of emissions. For practical application, products can still be aggregated into categories and used with average decay probability distributions that are considerable improvements over simple expressions such as first-order decay.

Conclusions

Given that there is a cost of carbon emissions and that the cost should be paid by someone, it can be reasonably argued that the cost should be paid at the time of carbon release. It is assumed that the cost of carbon emissions is initially b and increases at a constant continuously compounded annual rate r so that at time T this cost is $b_T = be^{ri}$. The cost of carbon emissions then becomes an expected present value calculation involving the probability density of carbon emissions with an inflation adjusted discount factor $\delta = \Gamma - r$, where Γ is the continuously compounded rate used for determining the time value of money.

In terms of LCA, it is clear that so long as carbon emissions have value, the time of emissions is important and emissions (or sequestration) at later times will have different value than current emissions. This difference in value will depend on the time lapse for the carbon emissions but also on the uncertainty in both the magnitude and timing of the emissions. For oxidation of a long-lived product, there will be no increase in uncertainty in the mass of carbon involved and we have only to deal with the time profile of carbon emissions. For carbon offsets or process-based emissions (e.g., fossil-fuel emissions related to end-of life management), the risk charge needs to address both the uncertainty in the emissions estimate (see Marland *et al.* [1]) and the uncertainty in its timing. Quantitative evaluation of risk charge is a challenge for actuarial science.

Executive summary

Background

- This article builds off of its companion article that highlights the merits and need for a risk charge based on the uncertainty of emissions in GHG accounting. This section sets that stage and outlines the purpose of this article, which is to outline the implications of using a risk charge on uncertainty in climate change. The introduction also outlines the literature which expresses the importance and difficulty in dealing with time properly.

Discounting & present values

- Introduces the concepts of discounting and present values. The use of discounting is justified – although this article recognizes that the discount rate may be zero in some cases. This section also introduces the basic notation needed for the rest of the article.

Time horizons & permanence

- Time horizons have been very contentious with claims that vary greatly on how to use them. This section also outlines the implications of time horizons, and what inherent assumptions are made about discounting and risk when various time horizons are incorporated.
- Permanence is introduced as an extension of a time horizon. The idea of a risk charge is then applied to several ideas that show how time horizons, whatever strategy is chosen, might be dealt with in a reasonable manner. This includes the idea of permanence, which is really just another phrasing of a time horizon.

Distributional approach to risk charges

- This section discusses a slightly different approach to risk charges in the context of a sensitivity analysis. The sensitivity here is based on the entire function of oxidation rather than on the individual parameters – this gives a much more consistent result if the functional form is changed. This replaces a standard parameter sensitivity and uses a sensitivity on the entire idea of oxidation. The argument is made that this approach more carefully deals with the fact that two different distributions that model a decay might have very different sensitivities to their parameters but have essentially the same form.

Trading time for space

- This section offers insight about the increased uncertainty of looking forward over long time periods and points out the merits of using spatial averaging in the current time to combat the uncertainties through time. The idea here is to keep the large uncertainties in time segregated from short-term calculations and near-term trades.

Agreement contract lengths

- This section outlines the need to balance setting long-term goals while keeping climate contracts (offset agreements) short to minimize uncertainties. This section builds off of the ideas in the trading time for space idea by showing how multiple short-term contracts and agreements reduces uncertainties created from extended time calculations.

Short-term storage

- The value of short-term storage has been controversial over the past 10 years. In the context of this article, the value of short-term storage resolves itself rather simply. If emissions have value, then converting to the common unit of money makes comparisons objective. There are still controversial topics related to this idea but the basic economic factors should hopefully be alleviated by this discussion.

Conclusions

- The conclusion is that risk charges allow a straight-forward and consistent way to deal with quantifying uncertainty. The examples have walked through many ways that this approach can resolve or simplify long standing controversies in a transparent way.

We admit that we do not know the cost of carbon emissions or how it will change in the future, but there is definitely emerging an economic value associated with carbon emissions and sequestration. In addition to the difficulty in placing a price tag on the value of emissions, it is an additional challenge to anticipate how that value will evolve over time. As the market progresses and matures, clearer estimates and projections should be possible.

Several clear connections can be made however. It is clear that uncertainty increases with time and that efforts to manage uncertainty can be aided by efforts to minimize the effects of time and discounting. Several ideas have been shown to alleviate the dependence on time: short contracts, trading space for time and limiting time horizons. Each of these relies on a reliable and consistent treatment of the uncertainties involved in the calculations.

Carbon emissions estimates can be dealt with in a consistent manner, with a risk charge beginning to define how we give economic value to uncertainty in commitments and transactions. The result is that an appropriate accounting system needs to include uncertainty and time. The first steps in doing this are to acknowledge that there is value in reducing uncertainty, and hence value in minimizing time steps and commitments over time.

We acknowledge that we cannot account for the future; we can only make promises for which the keeping has higher uncertainty the longer the time. However, the uncertainty of the future does not keep it from happening.

Future perspective

We feel that we have developed a very general approach to dealing with uncertainties in climate change accounting that has the potential for providing a common global approach. More work needs to be done in creating policies and hashing out details but we think that this article offers the foundational theory on which the policies can stand. We hope that this contribution will initiate the needed conversation that will drive the development of foundational theory to deal with uncertainty and time issues in accounting in climate policies.

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