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Estimates of the social cost of carbon have not changed over time

Richard Tol
University of Sussex
r.tol@sussex.ac.uk

Abstract: Some claim that as knowledge about climate change accumulates, the social cost of carbon increases. A meta-analysis of published estimates shows that this is not the case. Correcting for inflation and emission year and controlling for the discount rate, kernel density decomposition reveals a stationary distribution. Actual carbon prices are almost everywhere below the estimated social cost of carbon.

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May 8, 2021

Abstract

Some claim that as knowledge about climate change accumulates, the social cost of carbon increases. A meta-analysis of published estimates shows that this is not the case. Correcting for inflation and emission year and controlling for the discount rate, kernel density decomposition reveals a stationary distribution. Actual carbon prices are almost everywhere below the estimated social cost of carbon.

Main

The social cost of carbon is a key indicator of the seriousness of climate change. Have its estimates changed over time? Should we raise our ambitions to reduce greenhouse gas emissions? Have we learned since the first estimate was published in 1982[1]? I apply a non-parametric test for the stationarity of the probability distribution of published estimates of the social cost of carbon, and a range of other statistical tests, to show that we have, in fact, not.

The social cost of carbon is the damage done, at the margin, by emitting more carbon dioxide into the atmosphere. If evaluated along the optimal emissions trajectory, the social cost of carbon equals the Pigou tax[2] that internalizes the externality and restores the Pareto optimum.[3] The social cost of carbon is the optimal carbon price. It informs the desired intensity of climate policy.

Some have argued[4, 5] that the debate on optimal climate policy is over since the Paris Agreement has set targets for international climate policy. Analysis should focus on the cheapest way of meeting these targets, and emissions should be priced based on the *shadow price of carbon*, which is the scarcity value of the carbon budget.[4] However, the first stock-take of the commitments under the Paris Agreement[6] reveals that few countries plan to do what is needed to meet the agreed targets. The debate over the ultimate target of international climate policy, and so the debate on the social cost of carbon, is not over.

There is a large literature on the social cost of carbon spanning four decades[1, 7]. I count 5,791 estimates in 201 papers, published before April 2021. These are estimates of the social cost of carbon for carbon dioxide emitted in the recent past. The carbon tax should increase over time.[until climate change has been mitigated to the point that its marginal impacts start to fall 8] 93 papers estimate how fast, showing estimates of the social cost of carbon at two or more points in time, for a total of 1,972 estimates of the *growth rate* of the social cost of carbon.

I apply meta-analysis to these estimates. This is not the only way to make the social cost of carbon more transparent. Sensitivity analysis[9] and model comparison[10] are at least as insightful. Decomposition of model updates[11, 12] helps to understand the evolution of estimates, but only within the confines of a single model. Only meta-analysis can show how the entire literature has evolved over time.

Figure 1 shows the mean and standard deviation of estimates of the social cost of carbon by year of publication, as well as the standard error of the mean. Table 1 show the mean and standard deviation by pure rate of time preference. In this paper, estimates are expressed in 2010 US dollars per metric tonne of carbon, and are for emissions in the year 2010. The literature uses nominal dollars and a variety of emission years. See Figure S6. Particularly, later studies report the social cost of carbon in later dollars for later emission years. Average inflation was 2.9% over the period. The social cost of carbon grows by some 2.2% per year; this is the average across the 93 studies that estimate its growth rate. Without correcting for emission year and inflation, the *apparent* trend in the social cost of carbon equals 5.1% per year. After correction, some of the early estimates are the highest. Between 1993 and 2008, estimates went up and down without a discernible trend in either direction. Since 2009 or so, there appears to be an increase in the social cost of carbon, and three of the last four years stand out. An earlier meta-analysis finds that the social cost of carbon has not increased over time[13] but a more recent one finds that it has[14]. The mean for 2021 is higher than all but two other years; paired t-tests shows the 2021 mean is statistically significantly higher than all but four other years.

Everything about climate change is uncertain. An assessment of the literature of the social cost of carbon should reflect that uncertainty. Attention should be paid to the entire probability distribution rather than just its central tendency or its first and second moment. Figure 1 is incomplete.

Another problem with Figure 1 is that it invites an interpretation based on the implicit assumption of normality. This is inappropriate. The uncertainty about climate change is right-skewed.[15] This is the case for the uncertainty about climate sensitivity.[16] Non-linear impact functions amplify higher-than-expected warming over lower-than-expected climate change.[17] Risk aversion emphasizes negative surprises over positive ones.[18] Any confidence interval around the central estimate of the social cost of carbon is therefore asymmetric; this message is lost by adding and subtracting the standard deviation or error from the mean, as is done in Figure 1. The uncertainty about the social cost of carbon is thick- or even fat-tailed.[19] The mean plus the standard deviation does not equal the 83rd percentile. There is considerably more probability mass outside the normal bounds. The t-tests referred to above may be overconfident. If the distribution of the social cost of carbon is right-skewed and fat-tailed, then recent estimates may well be within the historical range.

Standard probability density functions do not adequately describe the uncertainty about the social cost of carbon, which is right-skewed and thick-tailed. Kernel densities are a flexible alternative to parametric distribution functions[20]. Kernel densities have been used to visualize the uncertainty about the social cost of carbon.[21] I here add many more observations, and decompose that uncertainty into discrete components, particularly publication periods, testing whether the components differ from one another. Simple kernel regression is helpful for specifying the relationship between two variables.[22] Kernel quantile regression can be used to show this relationship across the distribution.[23] However, these methods are not suitable if the explanatory variable is categorical—as is the case for discount rates or years of publication. The method proposed here, kernel density decomposition, works for categorical data, shows both central tendency and spread, and does not make assumptions about functional form or the shape of the probability distribution.

Kernel density decomposition therefore offer a more valid basis for statistical tests than the paired t-tests above, which assume normality. In order to test for changes over time, I split the sample into six periods, demarcated by important events in the publication history of the social cost of carbon. These key events are the Second Assessment Report of the Intergovernmental Panel on Climate Change[24], the Third Assessment Report of the IPCC[25], the Stern Review[26], the Obama update of the social cost of carbon[27], and the 2018 Nobel Memorial Prize in Economic Sciences.[28] These events reminded people of the importance of pricing carbon and stimulated new research into the social cost of carbon.

The kernel density is estimated with bespoke kernel functions, reflecting the deep and asymmetric uncertainty of the social cost of carbon. The data are weighted for quality; implausibly high estimates are censored. The decomposition of the kernel density is based on the fact that the weighted sum of probability densities is a probability density.[29] The statistical test is that for the equality of proportions.[30]. Applied to different publication periods, this is a test for the stationarity of the distribution[31] of the social cost of carbon. See *Methods* for the details, the *Supplementary Information* for sensitivity analyses.

Figure 2 shows the kernel density of the social cost of carbon and its the decomposition by publication period. The kernel density has the same shape as the histogram in Figure S1: There is a little probability mass below zero, a pronounced mode, and a thick right tail. Compared to the histogram, the kernel density is smooth and spread wider. This is also seen in Table 1: Kernel mean and standard deviation are larger than their empirical counterparts.

Earlier studies exclude negative estimates, but other patterns are not obvious from the kernel decomposition. Table S4 confirms this. It shows the contributions of estimates of the social cost of carbon published in a particular period to the overall kernel density and its quintiles. The quintile shares are statistically indistinguishable from the overall shares; $\chi^2_{20} = 12.77; p = 0.887$.

This analysis only considers time. Figure S7 shows that the discount rate used to estimate the social cost of carbon has varied over time. Particularly, the once popular pure rate of time preference of 3.0% has been largely replaced by 1.5%. This would increase the social cost of carbon. Table 1 and Figure S13 confirm this.

Table 2 therefore repeats the analysis for the four pure rates of time preference for which there are observations in every time period: 0%, 1%, 2% and 3% (see Table S1). Conditional on the pure rate of time preference, the Equality of Proportions test finds no statistically significant difference between the publication periods either. The Kolmogorov-Smirnov test finds the same for quintiles but suggests differences at a finer resolution (see Table S9).

Three more analyses are included in the Supplementary Material. These analyses assume normality of error terms, avoiding the asymmetry and thick tail that are a feature of the social cost of carbon but make upward trends hard to detect. The first additional analysis is a weighted linear regression of the social cost of carbon on the pure rate of time preference, which shows a highly significant coefficient, and the year of publication, which is insignificant; either result is independent of the weights used. See Table S14. In the second analysis, the linear time trend is replaced by a flexible time trend. Again, the effect of publication year is insignificant regardless of weights. See Figure S12. Thirdly, quantile regression is used. The pure rate of time preference is significant for almost all quantiles and weights; the year of publication for almost none. However, the social cost of carbon appears to increase over time if estimates are weighted for quality and attention is restricted to the central parts of the distribution. See Table S14. All together, the upward trend in Figure 1 is not because of greater pessimism about climate change, but because analysts have used lower discount rates.

In sum, some have claimed that estimates of the social costs of carbon have increased over time.[12, 32–34] There is an apparent upward trend because estimates are reported for later years, because of price inflation, and because later analyses tend to use lower discount rates. Correcting for these factors and properly accounting for the asymmetric, heavy-tailed uncertainty, there is no statistically significant time trend in published estimates of the social cost of carbon.

The main reason for this null result is that the uncertainty about the social cost of carbon is very large. Research continuously refines our knowledge and updates our estimates, sometimes upwards, sometimes downwards. There are still many things left to research[35] and left to improve in our estimates.[36, 37] However, the social cost of carbon reflects the impact of future climate change and the future is as uncertain now as it was then.

The implication of the meta-analysis presented here is that the literature on the social cost of carbon does not justify an upward revision of carbon prices emission reduction targets. At the same time, the literature, summarized in Table 1, suggests that, in most of the world, the price of carbon is too low.[38] There is often a gap between the announced emissions targets and the policies supposed to achieve the targets.[6] Instead of raising the social cost of carbon, the *recommended* carbon price, attention should focus on raising the *actual* price of carbon.

PRTP	empirical	kernel
3%	41 (51)	77 (74)
2%	252 (544)	727 (705)
1%	148 (269)	393 (473)
0%	375 (494)	767 (745)
all	177 (377)	502 (550)

Table 1: Empirical and kernel average (standard deviation) of estimates of the social cost of carbon by pure rate of time preference (PRTP).

	χ^2_{20}	**p**
All	12.7726	0.8869
PRTP = 0%	0.9577	1.0000
PRTP = 1%	7.8782	0.9926
PRTP = 2%	16.3455	0.6950
PRTP = 3%	13.8335	0.8388

Table 2: Test for the equality of quintiles between publication periods for the whole sample and for selected pure rates of time preference.

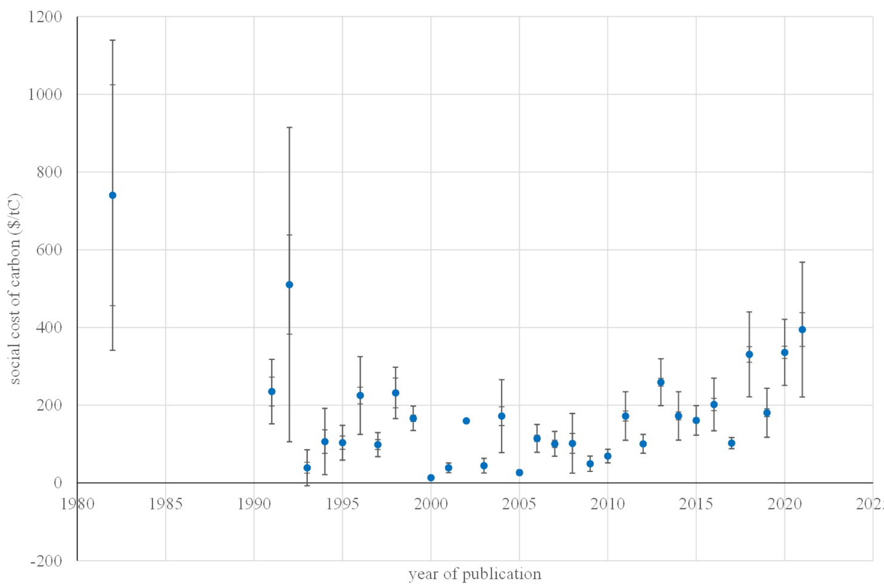

Figure 1: Average social cost of carbon by publication period. Outer error bars are plus and minus the standard deviation of the published estimates, inner error bars plus and minus the standard error of the mean. Estimates are quality weighted and censored.

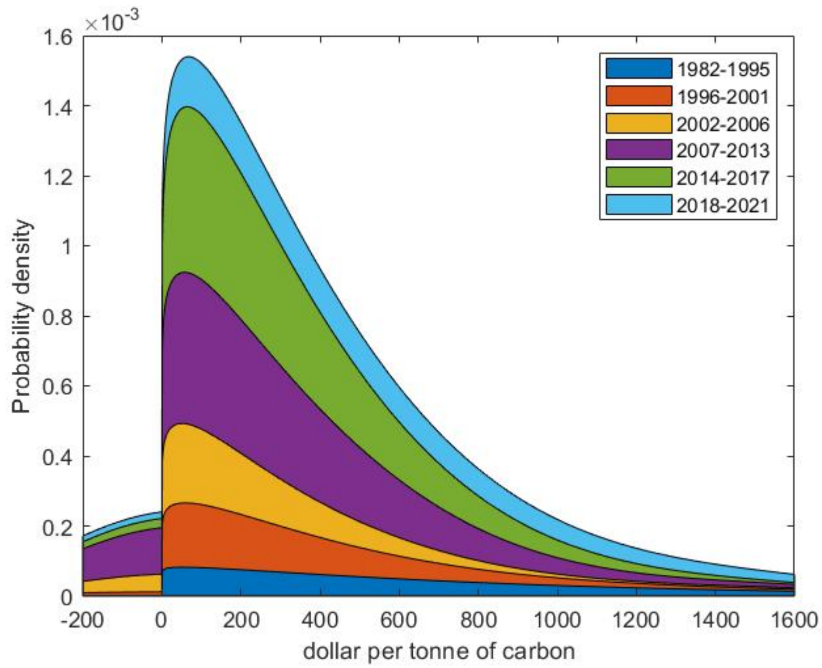

Figure 2: Kernel density of the social cost of carbon and its composition by publication period.

Methods

Kernel density decomposition

A *kernel density* is defined as

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{1}$$

where x_i are a series of observations, h is the bandwidth, and K is the *kernel function*. The kernel function is conventionally assumed to be a (i) **non-negative** (ii) **symmetric** function that (iii) **integrates to one**, with (iv) **zero mean** and (v) **finite variance**.[20] That is, any standardized symmetric probability density function can serve as a kernel function. The Normal density is a common choice.

Conventions are just that. As long as the kernel function is non-negative (the assumption of non-negativity is relaxed for bias reduction.[39]) and integrates to one, an appropriately weighted sum of kernel functions is non-negative and integrates to one—such a sum is a probability density function.[29, 40, 41]

The kernel density is defined thus defined as the sum of probabilities; see Equation (1). It is a vote-counting procedure[42] where the votes are uncertain. This interpretation fits the nature of the data. Estimates of the social cost of carbon are not "data" in the conventional sense of the word, nor can integrated assessment models be seen as "data generating processes". Besides, I use the population of estimates rather than a sample. There is therefore no Frequentist interpretation of the proposed method. There is no Bayesian interpretation either. While we might take the kernel function to express degrees of belief, a Bayesian procedure would take the first estimates[1] as prior and later estimates as likelihoods, *multiplying* rather than *adding* probability densities.

A kernel density can also be seen as a mixture density.[43, 44]. This reinterpretation opens a route to decomposition. We can construct the kernel density of any subset of x_i. The weighted sum of the kernel densities of the subsets is a kernel density.

With the right weights and bandwidths, the weighted sum of the kernel densities of subsets of the data is *identical* to the kernel density of the whole data set. To see this, partition the observations into m subsets of length m_j with $\sum_j m_j = n$, as $x_1, ...x_{m_1}, x_{m_1+1}, ..., x_{m_1+m_2}, x_{m_1+m_2+1}, ..., x_n$. Then

$$f(x) = \sum_{j=1}^{m} \frac{m_j}{n} \frac{1}{m_j h} \sum_{i=\sum_{k=1}^{j-1} m_k+1}^{\sum_{k=1}^{j} m_k} K\left(\frac{x - x_i}{h}\right) =: \sum_{j=1}^{m} \frac{m_j}{n} f_j(x) \tag{2}$$

This is identical to Equation (1). Moreover, each of the components f_j of the composite kernel density f is itself a kernel density.

Kernel decomposition works with any set of weights that add to one, and with any kernel function or bandwidth for the subsets:

$$f(x) = \sum_{j=1}^{m} \frac{w_j}{m_j h_j} \sum_{i=\sum_{k=1}^{j-1} m_k+1}^{\sum_{k=1}^{j} m_k} K_j \left(\frac{x - x_i}{h_j} \right) =: \sum_{j=1}^{m} w_j f_j(x; h_j) \tag{3}$$

In this case, the composite kernel density is not be the same as the kernel density fitted to the complete data set. It is hard to argue for different kernel functions K_j for different subsets of the data, but different subsets of the data would have different spreads and hence bandwidths h_j.

Inference

Equation (3) holds that the kernel density $f(x)$ is composed of m kernel densities $f_j(x)$ with weight m_j/n. For each interval $\underline{x} < x < \bar{x}$, I test whether the shares of the component densities equal its weight, using the Equality of Proportions test.[30] Suppose, for example, that a component density makes up 17% of the overall density. Then, the null hypothesis is that the left-tail, central part and right-tail of the component density also make up 17% of the left-tail, central part and right-tail of the overall density.

Let intervals correspond to p percentiles of the composite distribution. The test statistic is

$$\chi^2_{(m-1)(p-1)} = \frac{n}{p} \sum_{k=0}^{p} \sum_{j=1}^{m} \frac{\left(\int_{P_k}^{P_{k+1}} f_j(x) \mathrm{d}x - \frac{m_j}{n} \right)^2}{\frac{m_j}{n}} \tag{4}$$

The test only works if there are two components or more, $m \geq 2$. If not, there would be nothing to compare. The distribution needs to be split in two quantiles or more, $p \geq 2$, because each component density adds up to its weight m_j/n by construction. Again, there would be nothing to compare with fewer than two quantiles.

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Supplementary materials: Data and methods

Papers used in the meta-analysis

The database draws on earlier meta-analyses of the social cost of carbon,[1–6] extended with recent papers that were found using search engines and a review of the publication records of active researchers. 201 papers were used.[7–207] The record is close to complete for papers published before April 2021.

Most of the papers report results in tabular format. Some only show results in graphs, but most authors emailed the underlying data upon request; if not, the Matlab routine GRABIT[208] was used to digitize the graphs.

The meta-analysis uses the estimate of the social cost of carbon, the year of emission, the year of the nominal dollar, the year of publication, the author, weights, censoring, and the pure rate of time preference. These data, plus some not used here, can be found on GitHub.

Descriptive statistics

Table S1 shows the number of estimates per publication period and discount rate, and the number of papers per period. Three papers are counted double because they present comparative results of two different models. There is an upward trend in the number of papers per period, and in the number of estimates per paper.

Table S2 shows the mean and standard deviation of the estimates of the social cost of carbon by publication period and year. The range of estimates has grown very wide in recent years.

Figure S1 shows the histogram of the published estimates of the social cost of carbon, using quality weights and censoring (see below). Some estimates are negative, a social benefit of carbon, but the vast majority is positive. The mode lies between 0 and \$50/tC, but there is a long right tail. The 95th percentile is \$800/tC.

Bandwidth and kernel function

The choice of kernel function and bandwidth is key to any kernel density estimate, as illustrated in Figure S2. If kernel density estimation is interpreted as vote-counting, kernel and bandwidth should be chosen to reflect the nature of the data, shown in Figure S1. In this case, the uncertainty about the social cost of carbon is large and right-skewed. Furthermore, the social cost of carbon is, most researchers argue, a cost and not a benefit.

A conventional choice would be to use a Normal kernel function, with a bandwidth according to the Silverman rule[209], that is, 1.06 times the sample standard deviation divided by the fifth root of the number of observations. Figure S2 reveals two problems with this approach: The right tail of the resulting kernel density is thin, and a large probability mass is assigned to negative social costs of carbon. If the bandwidth equals the sample standard deviation to reflect the wide uncertainty, the right tail appropriately thickens but the probability of a Pigou subsidy on greenhouse gas emissions increases too.

Many of the published estimates of the social cost of carbon are based on an impact function that excludes benefits of climate change. Climate change can only do damage and additional carbon dioxide can only be bad. Honouring that, I assign a *knotted* Normal kernel function to these observations. As the kernel function is **asymmetric**, centralization needs to be carefully considered—is x_i in Equation (1) the mean, median or mode of K? I prefer to use the mode as its central tendency, in line with the interpretation of kernel density estimation as vote-counting (see below). With these assumptions, Figure S2 shows that the probability of a negative social cost of carbon falls.

The studies that report the possibility of a negative social cost of carbon nonetheless argue in favour of a positive one. A symmetric Normal kernel does not reflect that. I therefore replace it with a Gumbel kernel:

$$f(x) = \frac{1}{\beta} \exp\left(-\frac{x-\mu}{\beta} - \exp\left(-\frac{x-\mu}{\beta}\right)\right) \tag{S1}$$

The Gumbel distribution is defined on the real line but right-skewed. Again, I use the mode μ as its central tendency. This thickens the right tail and thins the left tail.

A knotted Normal kernel is not only peculiar near zero but it also has a thin tail. I therefore replace it with a Weibull kernel:

$$f(x) = \frac{\kappa}{\lambda} \left(\frac{x}{\lambda}\right)^{\kappa-1} \exp\left(\left(\frac{x}{\lambda}\right)^{\kappa}\right) \tag{S2}$$

The Weibull is defined on the *positive* real line, $f(x)$ is near zero if x is near zero, and right-skewed. I use the mode $\lambda \left(\kappa - {}^{1}\!/_{\kappa}\right)^{1/\kappa}$ as its central tendency. The right tail of the kernel distribution thickens again. The Weibull-Gumbel kernel distribution is the default used here.

The Matlab code can be found on GitHub.

Weights

The social cost of carbon is an estimate of the willingness to pay to reduce carbon dioxide emissions. Willingness to pay is limited by ability to pay. 282 out of 5,397 estimates violate this. If the estimated social cost of carbon were levied as a carbon tax, tax revenue would exceed total income. This is not possible. These estimates, exceeding \$7,609/tC (the global average carbon intensity in 2010), are excluded.

Another 1,186 estimates are so large that, if levied as a carbon tax, the public sector would grow beyond its global average of 15% in 2010, even if all other taxes would be abolished. Estimates in excess of this Leviathan tax[210], \$1,141/tC, are discounted. The discount is linear, varying between 0 for \$1,141/tC and 1 for \$7,609/tC. Without these discounts, very large estimates of the social cost of carbon dominate the analysis; cf. Table S2.

The estimates of the social cost of carbon are weighted in three different ways. First, all estimates are treated equally. This is graph "no weights" in Figure S3. While some papers present a single estimate of the social cost of carbon, other papers show many, up to 1,229 variants[207]. This emphasizes studies that ran many sensitivity analyses, which became easier as computers got faster. Secondly, estimates are weighted such that the total weight *per paper* equals one. This is "paper weights" in Figure S3. Within each paper, estimates that are favoured by the authors are given higher weight. Favoured estimates are highlighted in the abstract and conclusions, and they are used as the starting point in robustness checks. Estimates that are shown in order to demonstrate that the new model can replicate earlier work are not favoured. This is "author weights" in Figure S3.

Different experts have cast different numbers of votes. I count one paper as one vote. One can also argue that it should be one vote per expert, or that papers should be weighted by citations, journal prestige, or author pedigree. Composite kernel densities naturally allow for this, but it is a dangerous route to travel in this case. Older papers are cited more than younger papers; journal rankings are hard enough within disciplines, harder still between disciplines; and prestige, reputation and pedigree often reflect old glory rather than current wits.

Instead, I use a set of weights that reflect the quality of the paper. Over 95% of the estimates are peer-reviewed; these score 1; the rest score 0. Almost 95% use an emission scenario; these score 1; papers based on arbitrary emissions score 0 as do papers assuming a steady state. Almost 99% of estimates estimate the social cost of carbon as a true marginal or a small increment; these score 1; papers with ropy mathematics score 0 as do papers reporting an average rather than a marginal. Over 68% of estimates assume that vulnerability to climate change is constant; these score 0; papers that recognize that the impacts of climate change vary with development score 1. Only 3% of estimates is based on new estimates of the total impact of climate change; these score 1; the rest score 0. These scores are added. This is "quality weights" in Figure S3.

Figure S3 shows the impact of the weights. The censoring of large estimates, in excess of the Leviathan tax or even in excess of income, has the largest effect. The maximum estimate in the data is $107,260,751/tC. Including estimates like these, the kernel bandwidth becomes so large that the kernel density becomes almost uniform.

The censored data reveal an articulated probability density function. The unweighted estimates have the fattest tail; that is, papers that are more pessimistic about climate change present more estimates of the social cost of carbon. Giving every paper, rather than every estimate, a unit weight thins the right tail. Discounting estimates that their own authors discount further thins the tail. This result is mechanical, as the convention in sensitivity analysis is to show both high and low alternatives to the central assumptions. Quality weights thin the tail further still. More credible studies are less pessimistic.

Uncertainty about uncertainty

The kernel density describes the uncertainty about the social cost of carbon. The kernel density is an estimate and as such uncertain. Above and below, I ignore the uncertainty about the uncertainty. Figure S4 shows the 95% confidence interval around the Weibull-Gumbel kernel distribution of Figure S2, using quality weights as in Figure S3. This confidence interval is based on a bootstrap of 1,000 replications of the published estimates (without reweighing).

The shape of the kernel distribution is well-defined. The key uncertainty is about the weight of the tail relative to the central part of the distribution.

Ignoring the uncertainty about the uncertainty makes it *more* likely to detect patterns. As I find that the primary uncertainty is too large to detect changes over time, ignoring secondary uncertainty does not affect the results. I therefore proceed without the computationally expensive bootstrap and without the conceptually challenging meta-uncertainty.

Publication bias

Publication bias in the literature on the social cost of carbon has been reported [211]. Standard tests for publication bias are designed for statistical analyses, particularly test for a reluctance to publish insignificant results. The reported "publication bias" thus reflects that few studies report *negative* estimates of the social cost of carbon. Indeed, in the original DICE model [14], the social cost of carbon is positive *by construction* (see above). Many later papers follow in Nordhaus' footsteps. The reported *publication* bias is perhaps better interpreted as *confirmation* bias.

A recently proposed test for publication bias[212] is more general and can be applied to non-statistical results. The null hypothesis is that earlier and later studies are drawn from the same distribution. If not, later studies are influenced by earlier results—a sign of publication bias. The test used here is similar in spirit—does the distribution change over time—but the interpretation is about the knowledge base rather than the publication practice. It is not possible to disentangle changes in knowledge from changes in publication.

Supplementary materials: Results

The growth rate of the social cost of carbon

Different studies report the social cost of carbon for different years of emission. Estimates are standardized to emissions in the year 2010, assuming that the social cost of carbon grows by some 2.2% per year. That is, estimates for 2000, say, are multiplied by 1.022^{10} and estimates for 2020 are divided by the same factor. This correction factor is the same for all studies and for all estimates.

Figure S5 shows the kernel density of the growth rate of the social cost of carbon, decomposed for the pure rate of time preference. The density is symmetric for a 3.0% utility discount rate. However, for discount rates of 1.5% and 2.0%, little probability mass is added to the left tail, and a lot to the right tail.

Table S3 shows the shares by quintile of the kernel density. The same pattern is seen as in the graph, but Pearson's test does not reject the null hypothesis that the component densities are equal to the composite one; $\chi^2_{24} = 3.50; p = 1.000$. This justifies the assumption of a uniform growth rate of the social cost of carbon.

Time and discount

Table S4 and Figure 2 show that the distribution of the social cost of carbon has not significantly changed over time. Figure S7, however, reveals that the pure rate of time preference used to estimate the social cost of carbon has changed over time. Notably, a 1.5% pure rate of time preference was first used in 2011 and became the dominant choice in later years.

I therefore redo the decomposition per period for four alternative pure rates of time preference, 0%, 1%, 2%, and 3%, which have been used throughout the period. Tables S5, S6, S7 and S8 and Figures S8, S9, S10 and S11 show the detailed results, Table 2 the summary. The null hypothesis that the six periods show the same probability density function for the social cost of carbon cannot be rejected regardless of the choice of pure rate of time preference.

Alternative non-parametric tests

Pearson's equality of *proportions* test is designed to compare the distributions of subsamples to the distribution of the whole sample. Alternatively, the subsample distributions can be scaled up to sum to one, and tests for the equality of *distributions* can be applied. However, for most of these tests, critical values are tabulated for specific null hypotheses only. These tests can be use to check whether the subsample distribution is, say, Normal but not whether it conforms to the whole-sample kernel distribution. The Kolmogorov-Smirnov test is the exception: Its test statistic converges to a known distribution, independent of the null hypothesis.[213] I did not use the tabulations.[214], instead computed the p-values.[215] Pearson's Equality of Proportions test considers the difference between entire distributions. The Kolmogorov-Smirnov test, on the other hand, consider the maximum deviation between distributions.

Table S9 shows the results. The null hypothesis that the quintiles of the subperiod distributions are equal to the quintiles of the distribution of the whole period, cannot be rejected. The equality of proportions test was applied to quintiles too. The two statistical tests agree.

The null hypothesis cannot be rejected for deciles and ventiles either. However, the null hypothesis is rejected for the third period if quinquagintiles are considered. For centiles, the null hypothesis is rejected for the first and third periods, and almost for the fourth and sixth. That is, the subperiod distributions are indistinguishable at a crude resolution but differences appear at a finer scale.

Tables S10 to S13 repeat the analysis, splitting the sample by discount rate and time period. Rejections of the null hypothesis are common, also for quintiles and deciles. However, Table S1 reveals that cell-sizes can be small, down to five estimates. With so few observations, confidence in the estimated kernel densities is low. Nonetheless, the more discerning Kolmogorov-Smirnov test points to changes over time that the Pearson test cannot detect.

Parametric tests

Table S14 shows the results for the weighted linear regression, based on the conventional assumptions of linearity and normality, of the social cost of carbon on the pure rate of time preference and the year of publication, using paper, author and quality weights. The time trend is not statistically significant from zero.

I repeat the analysis using year fixed effects rather than a linear time trend. Figure S12 shows the estimated time dummies, measuring the deviation from 1982. The dummies do not show a trend.

Table S14 also shows the results of quantile regressions, for quintiles as above. The time trend is insignificant for paper and author weights. Using quality weights, the time trend is positive and significant at the 5% level for the three lower quintiles. That is, lower estimates of the social cost of carbon are gradually disappearing from the higher-quality literature.

Discount rate

The social cost of carbon is the net prevent value of the additional future damages done by emitting slightly more carbon dioxide. The assumed discount rate is obviously important in its calculation.

Figure S13 decomposes the kernel density of the social cost of carbon into its components by pure rate of time preference used. "Other" refers to a range of numbers and methods, including constant consumption rates, various forms of declining discount rates, and Epstein-Zin preferences. As one would expect, the lower discount rates contribute more to the right tail of the distribution.

Table S15 shows the contributions of estimates of the social cost of carbon using a particular pure rate of time preference to the overall kernel density (denoted "null") as well as to the five quintiles of that density (denoted Q1-5). The null hypothesis that all shares are equal is firmly rejected; $\chi^2_{24} = 50.69; p = 0.001$.

This result justifies splitting the sample by discount rate. It also demonstrates that the Pearson test for the Equality of Proportions has the power to reject null hypotheses for these data and these kernel densities.

Author

I also test whether different researchers reach different conclusions, one test of the impact of subjective judgements on estimates of the social cost of carbon.

The decomposition of the kernel density by author opens another interpretation of kernel densities: Vote-counting.[216] Different experts have published different estimates of the social cost of carbon. These can be seen as votes for a particular Pigou tax. But as the experts are uncertain, they have voted for a central value and a spread. The kernel function is a vote, the kernel density adds those votes. Note the difference with Bayesian updating, which multiplies rather than adds probabilities.

I spit the sample into estimates by those who have published ten papers or more (i.e., Christopher W. Hope, William D. Nordhaus, Frederick van der Ploeg, Richard S.J. Tol) and others.

Figure S14 decomposes the kernel density by author. Of the named authors, estimates by van der Ploeg are the narrowest, Tol contributes most to the left tail, and Hope to the right tail.

Table S16 shows the contributions of estimates of the social cost of carbon published by a particular author to the overall kernel density and its quintiles. There are patterns in figure and table, and the null hypothesis that the quintile shares are indistinguishable from the overall shares cannot be rejected; $\chi^2_{16} = 20.42; p = 0.202$.

This justifies that the sample is split by period and discount rate, rather than by period, discount rate, and author.

	1982-1995	**1996-2001**	**2002-2006**	**2007-2013**	**2014-2017**	**2018-2021**	**total**
3.0%	33	27	39	108	24	106	337
2.0%	5	7	14	7	139	313	485
1.5%	0	0	0	38	216	1679	1933
1.0%	8	16	28	100	190	448	790
0.1%	0	4	1	21	69	121	216
0.0%	68	5	33	43	124	262	535
other	12	25	26	317	287	828	1495
# estimates	126	84	141	634	1049	3757	5791
# papers	19	18	23	51	52	41	204

Table S1: Number of papers on the social cost of carbon by publication period and the number of estimates by period and pure rate of time preference.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021	all
3.0%	23 (14)	65 (88)	25 (24)	25 (17)	53 (27)	131 (50)	43 (53)
2.0%	37 (18)	53 (26)	66 (47)	124 (113)	179 (144)	1042 (1212)	220 (588)
1.5%				205 (560)	1659 (12318)	11328 (388584)	6350 (275486)
1.0%	439 (409)	92 (57)	100 (112)	181 (370)	186 (980)	13704 (158497)	1980 (57875)
0.1%		552 (325)	575	331 (439)	440 (1265)	466 (953)	417 (988)
0.0%	408 (746)	867 (439)	448 (548)	385 (1102)	1608 (3083)	1509 (2903)	561 (1313)
other	1010 (1725)	466 (659)	119 (112)	162 (178)	184 (332)	28025 (1318717)	5067 (548248)
all	392 (994)	217 (433)	143 (297)	158 (395)	631 (6553)	14454 (744232)	3177 (333710)

Table S2: Average (standard deviation) of estimates of the social cost of carbon by publication period and pure rate of time preference.

	3.0	2.0	1.5	1.0	0.1	0.0	other
Q1	0.0696	0.0012	0.0129	0.0188	0.0050	0.0101	0.0789
Q2	0.0751	0.0040	0.0346	0.0172	0.0113	0.0023	0.0582
Q3	0.0416	0.0048	0.0647	0.0204	0.0053	0.0006	0.0615
Q4	0.0251	0.0056	0.0875	0.0244	0.0084	0.0011	0.0483
Q5	0.0323	0.0224	0.0780	0.0216	0.0067	0.0021	0.0388
Null	0.0487	0.0076	0.0555	0.0205	0.0073	0.0032	0.0571

Table S3: Observed and hypothesized contribution to the kernel density of the growth rate of the social cost of carbon by quintile and pure rate of time preference.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021
Q1	0.0086	0.0231	0.0365	0.0829	0.0566	0.0224
Q2	0.0126	0.0266	0.0298	0.0643	0.0704	0.0241
Q3	0.0135	0.0238	0.0231	0.0595	0.0624	0.0271
Q4	0.0156	0.0194	0.0152	0.0488	0.0491	0.0317
Q5	0.0295	0.0140	0.0068	0.0267	0.0260	0.0496
Null	0.0160	0.0214	0.0223	0.0564	0.0529	0.0310

Table S4: Observed and hypothesized contribution to the kernel density by quintile and publication period.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021
Q1	0.0286	0.0016	0.0880	0.0943	0.0082	0.0043
Q2	0.0380	0.0060	0.0756	0.0913	0.0198	0.0022
Q3	0.0294	0.0105	0.0733	0.0676	0.0252	0.0028
Q4	0.0220	0.0178	0.0653	0.0394	0.0314	0.0039
Q5	0.0119	0.0201	0.0553	0.0167	0.0325	0.0173
Null	0.0260	0.0112	0.0715	0.0618	0.0234	0.0061

Table S5: Observed and hypothesized contribution to the kernel density by quintile and publication period, for a pure rate of time preference of 0%.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021
Q1	0.0028	0.0332	0.0517	0.0802	0.0430	0.0198
Q2	0.0094	0.0833	0.0764	0.0450	0.0795	0.0201
Q3	0.0115	0.0170	0.0219	0.0482	0.0628	0.0199
Q4	0.0150	0.0008	0.0019	0.0548	0.0417	0.0181
Q5	0.0277	0.0000	0.0001	0.0862	0.0145	0.0137
Null	0.0133	0.0269	0.0304	0.0629	0.0483	0.0183

Table S6: Observed and hypothesized contribution to the kernel density by quintile and publication period, for a pure rate of time preference of 1%.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021
Q1	0.1510	0.2672	0.2229	0.0236	0.0785	0.0099
Q2	0.0000	0.0007	0.0071	0.0172	0.0856	0.0088
Q3	0.0000	0.0000	0.0000	0.0047	0.0377	0.0123
Q4	0.0000	0.0000	0.0000	0.0001	0.0034	0.0194
Q5	0.0000	0.0000	0.0000	0.0000	0.0007	0.0492
Null	0.0302	0.0536	0.0460	0.0091	0.0412	0.0199

Table S7: Observed and hypothesized contribution to the kernel density by quintile and publication period, for a pure rate of time preference of 2%.

	1982-1995	1996-2001	2002-2006	2007-2013	2014-2017	2018-2021
Q1	0.0587	0.0213	0.0621	0.1077	0.0055	0.0029
Q2	0.0725	0.0279	0.0760	0.1518	0.0120	0.0026
Q3	0.0149	0.0299	0.0500	0.0767	0.0203	0.0050
Q4	0.0001	0.0351	0.0147	0.0124	0.0165	0.0099
Q5	0.0000	0.0796	0.0022	0.0018	0.0016	0.0282
Null	0.0293	0.0387	0.0410	0.0701	0.0112	0.0097

Table S8: Observed and hypothesized contribution to the kernel density by quintile and publication period, for a pure rate of time preference of 3%.

	5	10	20	50	100
1982-1995	0.9984	0.9267	0.5850	0.0992	0.0049
1996-2001	1.0000	1.0000	0.9980	0.8388	0.4276
2002-2006	0.9833	0.7891	0.3586	0.0282	0.0004
2007-2013	1.0000	0.9950	0.8779	0.3460	0.0599
2014-2017	1.0000	0.9991	0.9466	0.4962	0.1269
2018-2021	1.0000	0.9968	0.8981	0.3828	0.0752

Table S9: p-values of Kolmogorov-Smirnov test statistic for the equality of the distributions of the period subsample and the whole sample (rows) for different discretizations of the distribution (columns).

	5	10	20	50	100
1982-1995	0.9372	0.5978	0.1876	0.0054	0.0000
1996-2001	0.2169	0.0177	0.0002	0.0000	0.0000
2002-2006	0.2562	0.0282	0.0004	0.0000	0.0000
2007-2013	1.0000	1.0000	0.9999	0.9427	0.6196
2014-2017	0.9991	0.9360	0.6172	0.1128	0.0063
2018-2021	1.0000	1.0000	1.0000	0.9978	0.9155

Table S10: p-values of Kolmogorov-Smirnov test statistic for the equality of the distributions of the period subsample and the whole sample (rows) for different discretizations of the distribution (columns), for a 0% pure rate of time preference.

	5	10	20	50	100
1982-1995	0.0009	0.0000	0.0000	0.0000	0.0000
1996-2001	0.0149	0.0000	0.0000	0.0000	0.0000
2002-2006	0.0149	0.0000	0.0000	0.0000	0.0000
2007-2013	0.1957	0.0133	0.0001	0.0000	0.0000
2014-2017	0.3288	0.0589	0.0015	0.0000	0.0000
2018-2021	0.7425	0.3145	0.0482	0.0002	0.0000

Table S11: p-values of Kolmogorov-Smirnov test statistic for the equality of the distributions of the period subsample and the whole sample (rows) for different discretizations of the distribution (columns), for a 1% pure rate of time preference.

	5	**10**	**20**	**50**	**100**
1982-1995	0.0009	0.0000	0.0000	0.0000	0.0000
1996-2001	0.0149	0.0000	0.0000	0.0000	0.0000
2002-2006	0.0149	0.0000	0.0000	0.0000	0.0000
2007-2013	0.1957	0.0133	0.0001	0.0000	0.0000
2014-2017	0.3288	0.0589	0.0015	0.0000	0.0000
2018-2021	0.7425	0.3145	0.0482	0.0002	0.0000

Table S12: p-values of Kolmogorov-Smirnov test statistic for the equality of the distributions of the period subsample and the whole sample (rows) for different discretizations of the distribution (columns), for a 2% pure rate of time preference.

	5	**10**	**20**	**50**	**100**
1982-1995	0.1995	0.0139	0.0001	0.0000	0.0000
1996-2001	0.9820	0.7568	0.3260	0.0218	0.0002
2002-2006	0.6867	0.2456	0.0303	0.0001	0.0000
2007-2013	0.4337	0.1078	0.0048	0.0000	0.0000
2014-2017	0.9998	0.9249	0.5714	0.0876	0.0034
2018-2021	0.3940	0.0829	0.0032	0.0000	0.0000

Table S13: p-values of Kolmogorov-Smirnov test statistic for the equality of the distributions of the period subsample and the whole sample (rows) for different discretizations of the distribution (columns), for a 3% pure rate of time preference.

weight	percentile	PRTP		year	
paper		-131***	(27)	-3.38	(3.64)
	0.1	-8.51**	(3.53)	0.457	(0.501)
	0.3	-17.3**	(7.6)	0.541	(1.074)
	0.5	-35.3***	(10.1)	0.866	(1.428)
	0.7	-75.3**	(32.1)	0.509	(4.557)
	0.9	-175	(161)	-2.05	(22.79)
author		-133***	(28)	-3.05	(3.54)
	0.1	-8.81**	(3.89)	0.643	(0.532)
	0.3	-15.7**	(7.3)	0.762	(0.995)
	0.5	-33.7***	(8.9)	1.05	(1.21)
	0.7	-71.4**	(28.0)	0.791	(3.822)
	0.9	-179	(184)	-1.72	(25.17)
quality		-104***	(16)	-0.0936	(2.1011)
	0.1	-7.41***	(1.86)	0.558**	(0.234)
	0.3	-9.97***	(2.48)	1.17***	(0.34)
	0.5	-33.0***	(3.8)	1.18**	(0.514)
	0.7	-62.0***	(10.4)	0.966	(1.419)
	0.9	-136***	(34)	4.36	(4.56)

Table S14: Results of weighted least squares and weighted quantile regression of the social cost of carbon on the pure rate of time preference and the publication year.

Standard errors are reported in brackets. Coefficients marked with ***, ** or * are statistically significant at the 1%, 5% or 10% level, respectively. The top row has results for the mean regression, the next five rows for the quantile regression for the indicated percentile.

	3.0	**2.0**	**1.5**	**1.0**	**0.1**	**0.0**	**other**
Q1	0.1461	0.0065	0.0354	0.0435	0.0048	0.0082	0.0511
Q2	0.0494	0.0089	0.0486	0.0350	0.0055	0.0063	0.0490
Q3	0.0043	0.0093	0.0448	0.0336	0.0063	0.0076	0.0547
Q4	0.0001	0.0103	0.0382	0.0295	0.0074	0.0101	0.0630
Q5	0.0000	0.0168	0.0246	0.0240	0.0094	0.0204	0.0872
Null	0.0400	0.0103	0.0383	0.0331	0.0067	0.0105	0.0610

Table S15: Observed and hypothesized contribution to the kernel density by quintile and pure rate of time preference.

	Hope	**Nordhaus**	**Ploeg**	**Tol**	**Other**
Q1	0.0185	0.0270	0.0205	0.0740	0.0882
Q2	0.0234	0.0261	0.0276	0.0405	0.1063
Q3	0.0212	0.0036	0.0247	0.0297	0.1120
Q4	0.0185	0.0000	0.0216	0.0163	0.1201
Q5	0.0094	0.0000	0.0176	0.0048	0.1485
Null	0.0182	0.0114	0.0224	0.0331	0.1150

Table S16: Observed and hypothesized contribution to the kernel density by quintile and author.

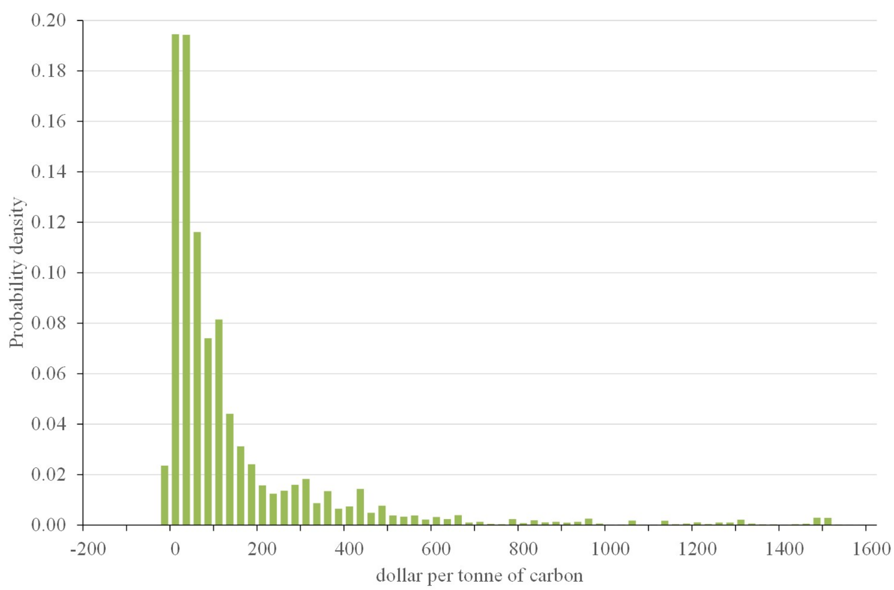

Figure S1: Histogram of the social cost of carbon. Results are quality-weighted and censored.

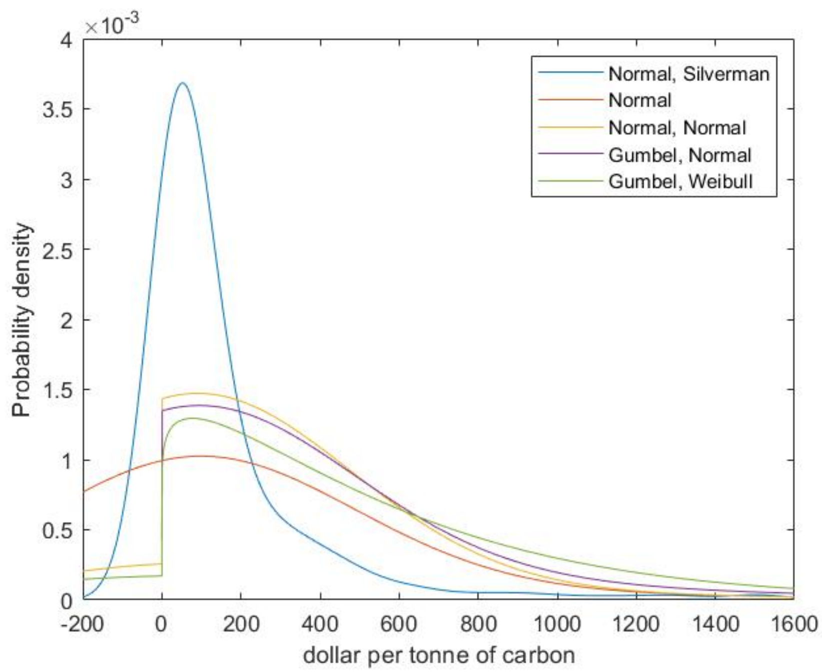

Figure S2: Kernel density of the social cost of carbon for alternative kernel functions and bandwidths.

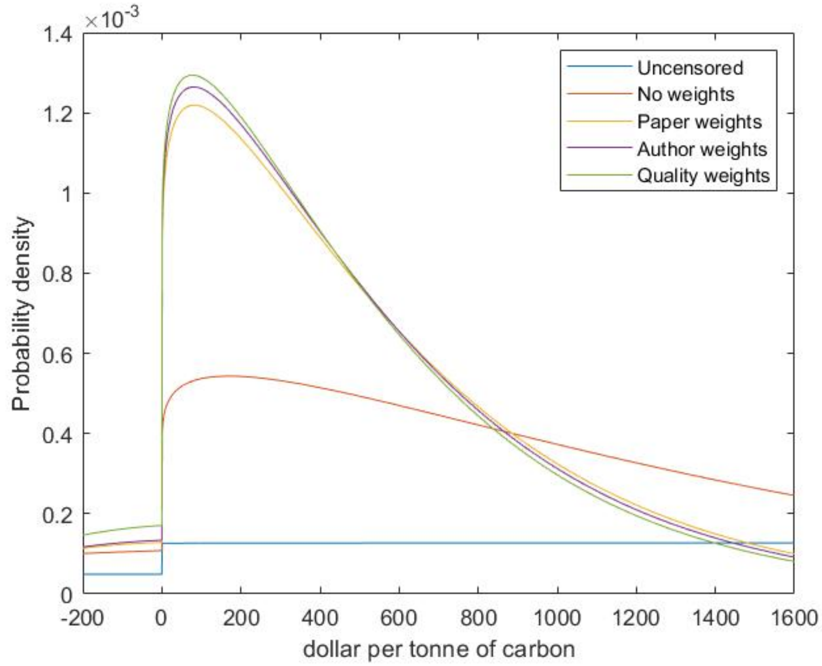

Figure S3: Kernel density of the social cost of carbon for alternative weights.

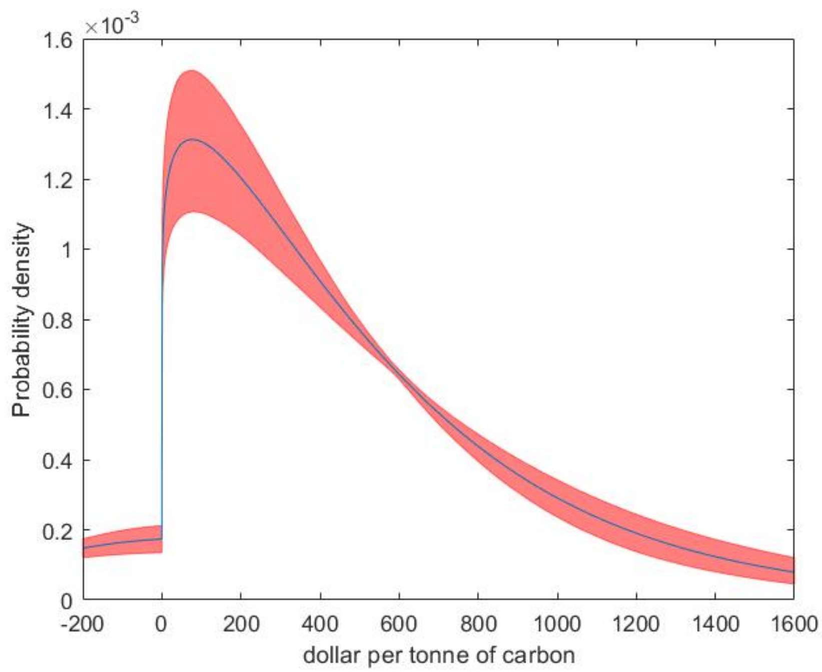

Figure S4: The 95% confidence interval of the kernel density of the social cost of carbon.

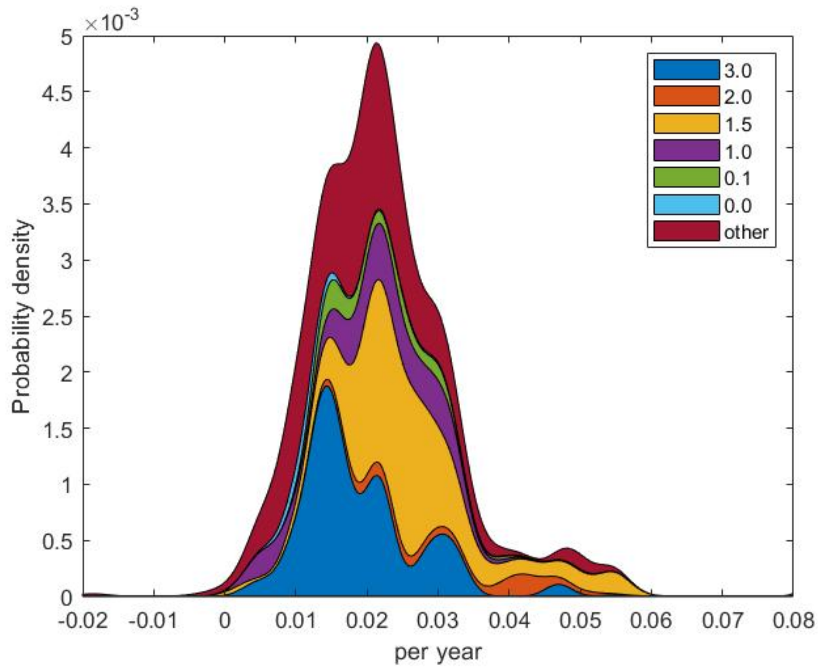

Figure S5: Kernel density of the growth rate of the social cost of carbon and its composition by discount rate.

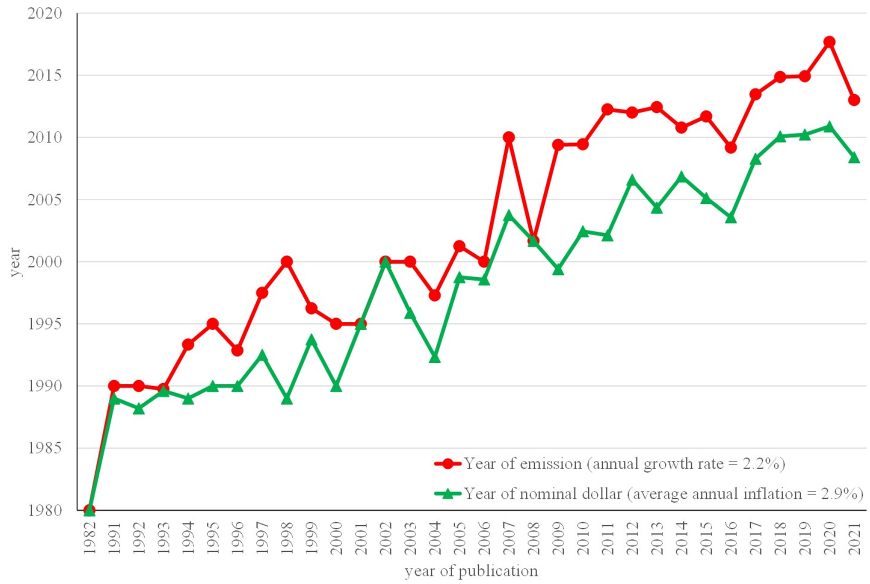

Figure S6: Year of emission and year of nominal dollar by year of publication. Estimates are weighted such that every published paper counts equally.

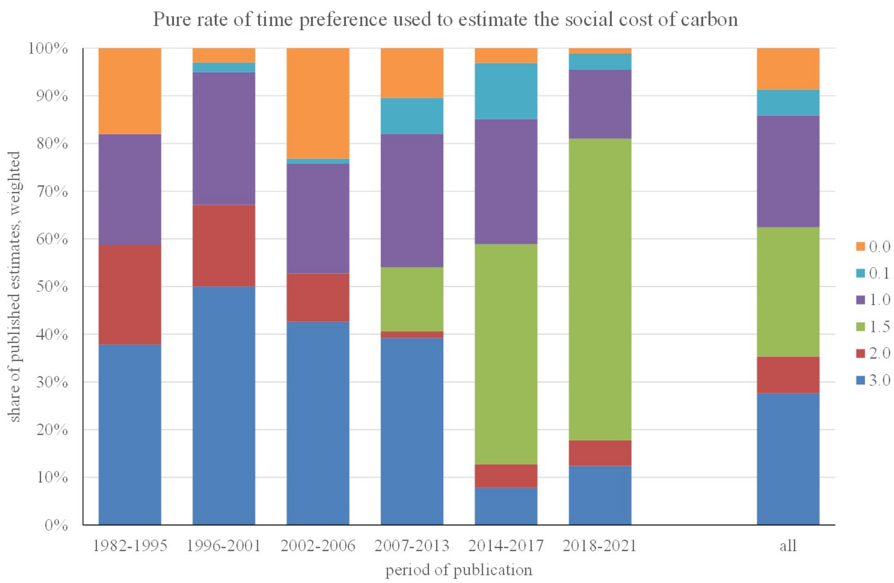

Figure S7: The pure rate of time preference used to estimate the social cost of carbon by publication period. Estimates are weighted such that every published paper counts equally.

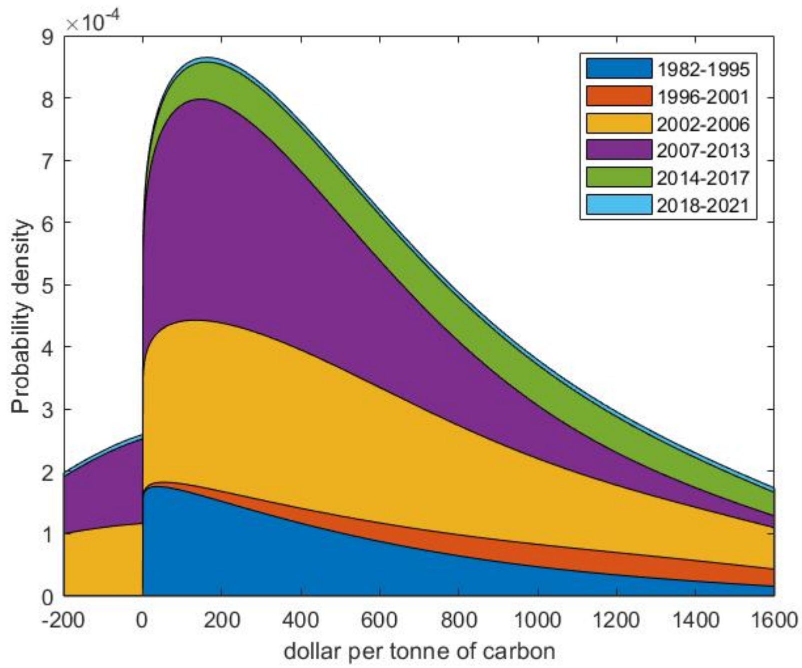

Figure S8: Kernel density of the social cost of carbon and its composition by publication period,for a pure rate of time preference of 0%.

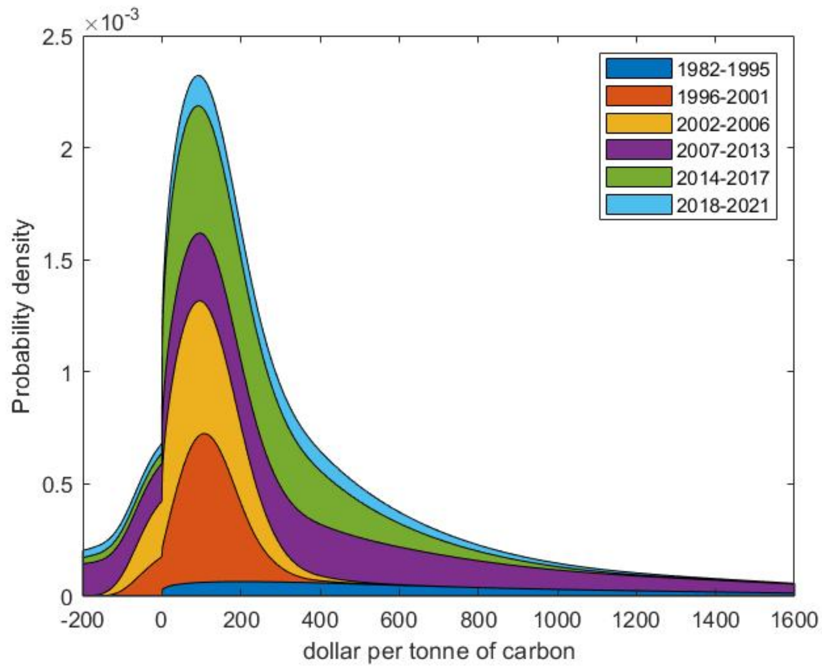

Figure S9: Kernel density of the social cost of carbon and its composition by publication period,for a pure rate of time preference of 1%.

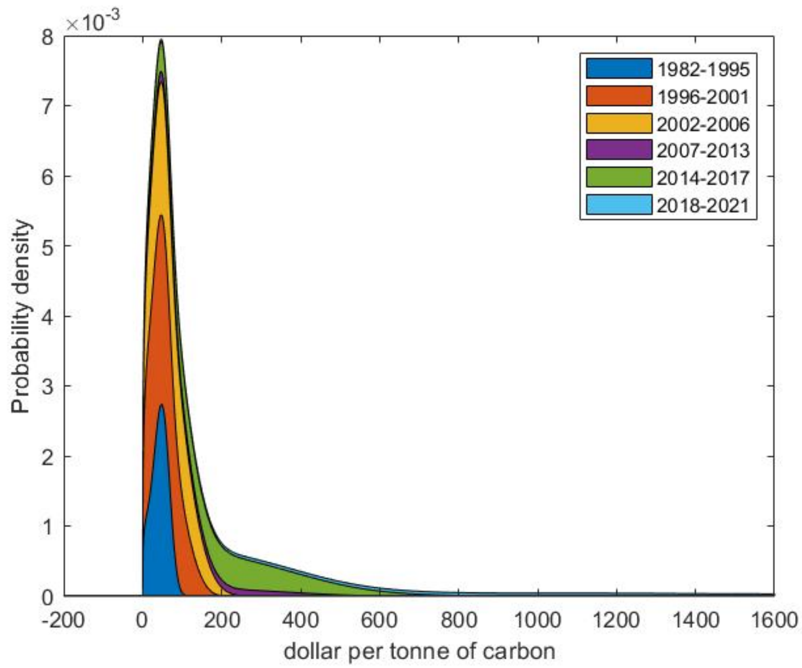

Figure S10: Kernel density of the social cost of carbon and its composition by publication period,for a pure rate of time preference of 2%.

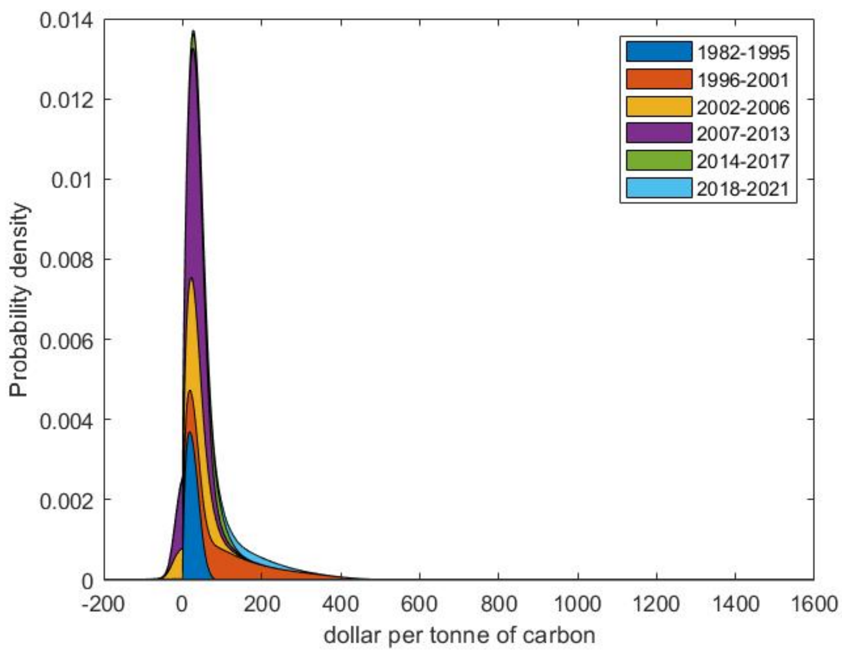

Figure S11: Kernel density of the social cost of carbon and its composition by publication period,for a pure rate of time preference of 3%.

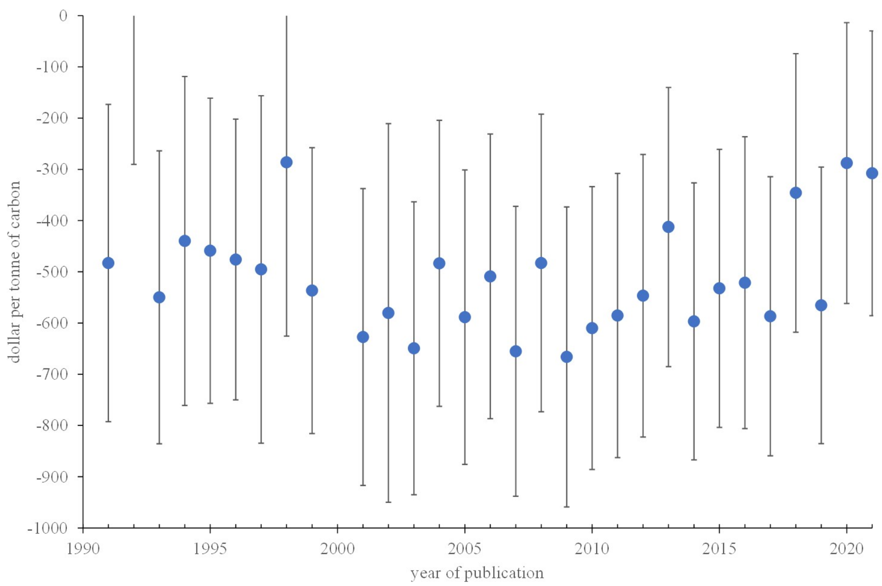

Figure S12: Year fixed-effects from a regression of the social cost of carbon on the pure rate of time preference, using quality weights. Base year is 1992; results for 1991 are not shown; error bars denote the 67% confidence interval.

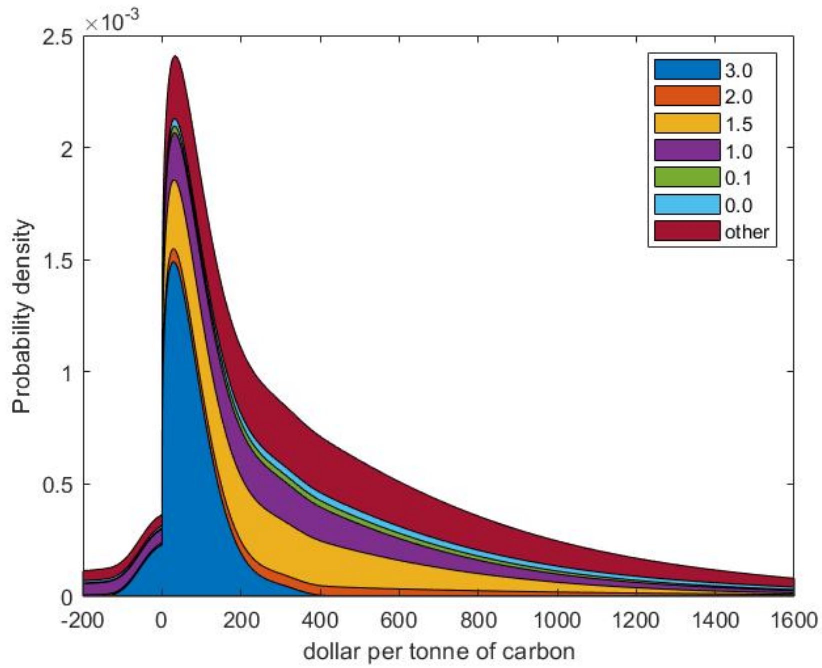

Figure S13: Kernel density of the social cost of carbon and its composition by the pure rate of time preference.

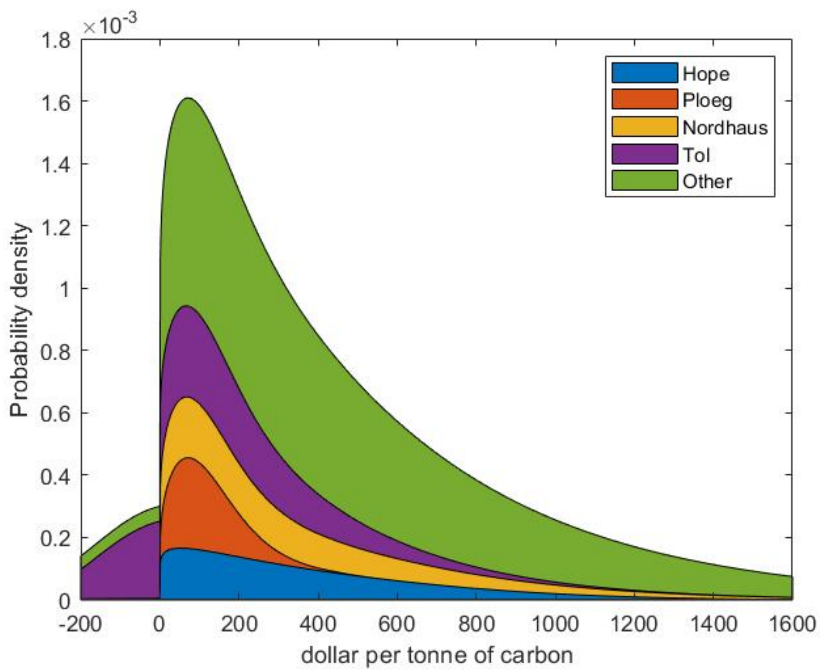

Figure S14: Kernel density of the social cost of carbon and its composition by author.

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