



Acceleration by climate change of global economic inflation

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Abstract. Regional climate anomalies have historically driven price increases that are followed by social conflict and economic decline. Integrated Assessment Model (IAM) studies of future climate damages to the global economy focus on the real (inflation-adjusted) GDP Y yet provide no direct guidance on the inflationary response. Here, we introduce a highly aggregated framework for the world economy in which inflation naturally emerges as an intrinsic rather than exogenous property of the macroeconomic system. A quantity “Wealth” is introduced defined as a single time-varying stock of historically cumulative, inflation-adjusted output $W(t) = \int_0^t Y(u)du$. Wealth grows with nominal output $Y_N = \beta W$ and shrinks with decay at rate γW , so that real output becomes $Y = (\beta - \gamma)W$. In this case, the inflation rate becomes $i = \dot{J}/(1 - J)$ where $J = \gamma/\beta$. Climate damages to Y represented by standard IAM quadratic damage functions are shown to scale with γ . But, even for high-end damages and global mean temperature increases, the inflation increment is small. However, global inflationary shocks cannot be ruled out. Wealth W has been tethered through a scaling factor to the world’s rate of primary energy consumption E . If climate change and other stresses redirect nominal output from civilization expansion to maintenance, and primary energy consumption relaxes from its current expansion rate of $\sim 2\%$ per year towards stagnation, then $J \rightarrow 1$. In this limit, stagflation and even hyperinflation emerge as key economic signatures of climate change, in line with historical evidence, and plausibly emerging this century.

15 Plain Language Summary

1 Introduction

Will future climate change drive global economic inflation? Empirically, local weather and climate extremes are known to lead to the combined outcome of substantial decreases in local economic output and concurrent reductions in welfare - defined as utility of consumption - resulting from price increases (Heinen et al., 2018; Bao et al., 2023; Jamilu Iliyasu and Ahmed, 2023). Reconstructions of economic and climate conditions during the pre-industrial era suggest that colder/drier phases, especially during the Little Ice Age, coincided with a sequential pattern of rising crop failures, inflation, warfare, and sharp population declines (Zhang et al., 2007). A Northern Hemisphere cooling anomaly of several tenths of a degree Celsius has been noted to coincide with dramatic grain price rises in China (Brook, 2023), Ottoman Anatolia (White, 2011), and Europe (Beveridge, 1921). Kotz et al. (2023) linked monthly consumer price index data from 121 countries to fluctuations in global meteorological reanalysis temperature datasets to find a non-linear response of inflation to temperature shocks with hotter



regions most affected. Extending their fit, projected warming was calculated to result in an increase in average headline inflation in the range of 0.32 to 1.18% per year by 2035, widening further by mid-century.

Integrated assessment models (IAMs) are the primary tools used to evaluate how future climate change will damage the economy. The advantage of these frameworks is that they offer a theoretical underpinning for a dynamic evaluation of GDP losses (Burke et al., 2015; Bjordal et al., 2022; Nordhaus, 2017; Kahn et al., 2021; Barrage and Nordhaus, 2024) or GDP growth (Moore and Diaz, 2015; Kotz et al., 2024). However, a limitation of many IAMs is that damages are typically expressed in terms of the real, i.e., *inflation-adjusted*, production, and so they do not offer any theoretical framework for estimating the inflationary response to climate warming.

As background, neoclassical accounting treats real (i.e., inflation-adjusted) economic output Y as a function of real capital K and labor L . The Cobb-Douglas function for real economic production is:

$$Y_0 = AK^{\bar{\alpha}}L^{(1-\bar{\alpha})} \quad (1)$$

For readability, we use a bar to denote parameters and coefficients that are assumed to be constant, such as the fixed exponent $\bar{\alpha}$ above, whereas all other quantities are implicitly assumed to be time-varying, but with the variable t omitted, for example the exogenously growing labor $L \equiv L(t)$. The subscript 0 in Y_0 denotes what could be expected absent current (not past) climate change. The efficiency factor A , or total factor productivity, is often attributed to technological innovation (Romer, 1994). Necessarily, because Y_0 has units of inflation-adjusted currency per time (for example, 2020 USD/year), A has units that are a function of the value of $\bar{\alpha}$. Normally, labor is assumed to grow exogenously.

Capital grows because a fraction s of actual annual output Y is saved and shrinks due to depreciation at rate δ :

$$\frac{dK}{dt} = sY - \delta K \quad (2)$$

Here actual output Y , taking into account climate change, is reduced from the undamaged output Y_0 that would be expected in the absence of warming. This is expressed as being in proportion to a damage function π defined such that:

$$Y = (1 - \pi(\Delta T))Y_0, \quad (3)$$

where ΔT represents a dynamic global temperature anomaly typically using the year 1850 as a reference. Most commonly, the damage function is assumed to take the form:

$$\pi = \frac{\bar{\varphi}\Delta T^2}{1 + \bar{\varphi}\Delta T^2} \quad (4)$$

A quadratic function is a simplification that has been hotly debated as it appears to exclude the potential for catastrophic economic damages that might arise from tipping points in the climate system and that might introduce a higher order temperature dependency (Burke et al., 2015; Dietz et al., 2021; Keen et al., 2022). Adopting Eq. 4, Estimates of π vary greatly, from a few percent for a 4°C temperature rise (Moore and Diaz, 2015; Nordhaus, 2017), to tens of percent by 2100 (Burke et al., 2015; Bjordal et al., 2022), or even 12 percent damage per 1°C (Bilal and Känzig, 2024). A primary reason for the uncertainty is statistical – collectively, at our current point in the global warming trajectory, the economy appears to have remained resilient



to the adverse impacts of climate change. Any damage “signal” is difficult to decouple from other driving factors (King et al., 2023), most notably the underlying temporal signal of GDP growth. More sophisticated IAMs further account for economic sectors and nations, including how they interact, either explicitly and dynamically, or implicitly through regionally derived expressions for the damage function. Climate damages are expected to be felt more strongly by lower-income countries (Burke et al., 2015), but globally, at least for the moment, overall GDP growth remains robust.

The goal here is to develop a very simple IAM that permits “back-of-the-envelope” analytical calculations of the forces driving future inflation and their relationship with the climate-damage function π defined above. We accomplish this by moving beyond the traditional neoclassical framework and introduce a highly aggregated mathematical identity analogous to physical capital that we term “Wealth” (capitalized to distinguish it from other possible interpretations of the word). An empirical relation is presented that ties Wealth to how fast the global economy consumes primary energy resources. We argue that in the long-run, global inflation will rise from increasing destruction of previously produced social and built infrastructure, and a consequent erosion of our collective capacity to access energy supplies. While existing estimates of π do not allow for very high inflation in the future, we show that very high inflation should be anticipated with stagnating GDP growth and stabilization of world energy consumption needs.

2 Inflation arising from damages to historically cumulative wealth

To develop an IAM that incorporates inflation, the first simplification we employ is to aggregate the global economy *spatially* as a whole, not as a collection of discrete nations and sectors. Such details multiply the necessary assumptions about how economic elements interact, increasing the range of possible climate change scenarios and interpretations (National Academies of Sciences and Medicine, 2024).

The second simplification we make is to aggregate the global economy *temporally* to include all of history. This offers both consistency with spatial aggregation and addresses a concern that physical capital K does not include all that is potentially affected by climate change. Piketty (2020) offers that “...the total value of public and private capital, evaluated in terms of market prices for national accounting purposes, constitutes only a tiny part of what humanity actually values - namely, the part that the community had chosen (rightly or wrongly) to exploit through economic transactions in the marketplace”. Expressed alternatively, the fractional contribution of output that constitutes an investment $I = sY$ in capital K excludes the broader wealth of humanity that cannot be sold but nonetheless supports real economic output Y . Ready examples might be the invention millennia ago of the number system or written text. These certainly required a financial investment to maintain and diffuse, and they boosted economic value by allowing for accounts to be tallied and for making records more permanent and communicable. But numbers and the alphabet cannot be marketed today – at the same time the modern economy would most certainly collapse if we no longer had access to them.

Aggregating capital to the maximum extent possible, both spatially and temporally, suggests a cumulative quantity W previously termed “Wealth” in Garrett (2011, 2014), for which the dynamic equation is:

$$\frac{dW}{dt} = Y \tag{5}$$



90 The integral form of Eq. 5 is the accumulation over history of prior real global economic output $Y(u)$ for $u \in [0, t]$:

$$W(t) = \int_0^t Y(u) du \quad (6)$$

By contrast with Eq. 2 for capital, Wealth in Eq. 5 represents the maximum possible global accumulation for a hypothetical case of $s = 1$ and $\delta = 0$. Along the lines of Piketty, the time integral W includes the full breadth of what we value as civilization's economic output – not only short-lived elements like sandwiches that we purchased for lunch but have not quite yet eaten, but also elements of culture like the alphabet that were created long ago and remain central to our economic success. Garrett et al. (2022) previously termed this broad accumulation of sociocultural and physical elements the “long arm of history”.

Because all real output adds to Wealth in Eq. 6, the expression might seem economically absurd. At the very least, it appears to lack the necessary sink term of depreciation present in Eq. 2. However, a sink term is implicit once we consider the difference between the continuous variables of nominal¹ output Y_N and real output Y . For this, observe that we can restate Eq. 5 as:

$$100 \quad \frac{dW}{dt} = Y_N - \gamma W \quad (7)$$

where, by substitution of Eq. 5

$$\gamma = \frac{Y_N - Y}{W} \quad (8)$$

Noting that typically (but not necessarily) $Y_N > Y$, we see that the term $\gamma W > 0$ corresponds to a sink term in the accumulation of W . In other words, as Wealth has been mathematically defined, all instantaneous nominal output is “saved” (namely, analogous to $s = 1$ in Eq. 2), but its net addition is offset by “decay” of Wealth at fractional rate γ . Effectively, γ represents the instantaneous decay rate of all that was previously produced and is still decaying now. Mathematically, one can consider that Wealth elements decay with varying times τ obeying a decay spectrum $\gamma(\tau)$ so that γ in Eq. 7 can be reexpressed as

$$\gamma = \frac{1}{W} \int_{t_0}^{\infty} \gamma_W(\tau) W(\tau) d\tau \quad (9)$$

where $W(\tau)$ is the amount of Wealth with remaining lifetime τ . As extreme examples, the spectral decay rate γ_W approaches zero for such long-lived bedrocks of humanity as the alphabet, and it becomes very large for a sandwich.

Eq. 5 can be reexpressed as

$$\frac{dW}{dt} = \beta W - \gamma W = \eta W \quad (10)$$

where:

$$\eta = \beta - \gamma, \quad \beta = \frac{Y_N}{W}, \quad \eta = \frac{Y}{W} \quad (11)$$

115 In summary $Y = \eta W$, $Y_N = \beta W$ and $Y_N - Y = \gamma W$. Effectively, β is a variable rate coefficient that represents the temporal efficiency of converting wealth into nominal output, which Garrett (2014) related previously to resource discovery and

¹Note that, unlike real output, nominal output cannot be directly integrated because the units of currency are specific to each year.



availability. Thus, $\eta = \beta - \gamma$ is the net output efficiency, in some ways similar to the total factor productivity A in Eq. 1 as a multiplicative factor on labor and capital, except that here it is applicable to a single variable W . This approach offers some elegance as the revised efficiency factor has a much simpler dimension than A in Eq. 1, namely of inverse time.

120 At this point in our argument, W , β and γ have only been introduced as mathematical creations that meet the simplifying criterion that all nominal output grows Wealth subject to Wealth decay, so that W , as defined, is the historical accumulation of world real output. The precise interpretation of W is only of passing importance at this point. That said, Wealth W tends to be much larger than capital K , which is somewhat the point: it includes the full history of real output, and so it extends far further than what Piketty termed the “tiny part” of what has been marketed and depreciated in recent memory. Using data taken from
125 the 50-year reference dataset described by Garrett et al. (2022), the ratio W/K was 13 in the year 2000 and 8.3 in 2019.

So, there are two important mathematical benefits of using Wealth W over capital K to study civilization evolution. First, the dynamic Eq. 5 is simple, requiring no assumptions about savings or depreciation rates. Accordingly, W serves a broader metric than K for representing what civilization has historically attained, and is likely better aligned with the totality of what could potentially be subject to climate damages. The second is that it simplifies treatments of GDP growth. Note how from Eq.
130 10, the instantaneous rate of exponential growth for Wealth is:

$$\frac{d \ln W}{dt} = \eta \quad (12)$$

Allowing that η itself might vary with time, and since $W = Y/\eta$, it follows that the real GDP growth rate is:

$$\frac{d \ln Y}{dt} = \eta + \frac{d \ln \eta}{dt} \quad (13)$$

or the sum of the growth rate of historically cumulative production W and the growth rate in the growth rate – what Garrett
135 (2015) previously termed the innovation rate. Instead of it being necessary to consider the time evolution of three variables for calculation GDP growth as for Eq. 1 (namely A , K and L), all that becomes necessary is one. Note that if the innovation term is positive, that is $d \ln \eta / dt > 0$, then GDP growth accelerates super-exponentially.

The third benefit is a ready link between decay and inflation. The instantaneous inflation rate i (dimensions of inverse time) is normally defined as the growth rate of the ratio of the nominal to the real output. Using Eq. 11, we find

$$140 \quad Y_N/Y = \beta/\eta = 1 + \gamma/\eta, \quad (14)$$

from which it follows that:

$$i = \frac{d \ln (Y_N/Y)}{dt} = \frac{d \ln (\beta/\eta)}{dt} = \frac{d \ln (1 + \gamma/\eta)}{dt} \quad (15)$$

or

$$i = \frac{d \ln \beta}{dt} - \frac{d \ln \eta}{dt} \simeq \frac{d}{dt} \left(\frac{\gamma}{\eta} \right) \quad (16)$$

145 For the case of slowly moving β , it follows that $i \simeq -d \ln \eta / dt$: inflation corresponds to a deceleration of real growth. From Eq. 13, this leads to the important implication that inflation and the inflation-adjusted real GDP are not independent – as one might



intuitively assume. In fact, inflation and stagnating GDP growth are coupled, what may be termed colloquially as stagflation. Accordingly, inflation might well be related to accelerating decay from natural disasters, or to any negative impact on real GDP growth rates.

150 3 The relationship of the climate-damage function to inflation

If we now define a baseline decay rate γ_0 as the analogue of Eq. 8 for undamaged production Y_0 , namely

$$\gamma_0 = \frac{Y_N - Y_0}{W}, \quad (17)$$

we can rewrite the total decay rate γ as a contribution γ_{cc} from climate damages in addition to γ_0 :

$$\gamma = \gamma_0 + \gamma_{cc}. \quad (18)$$

155 Defining further $\eta_0 = Y_0/W$ and substituting Eqs. 8 and 17 in Eq. 18, it follows that from which it follows that

$$\eta = \eta_0 - \gamma_{cc}. \quad (19)$$

On the other hand, dividing both sides of from Eq. 3 by W we obtain that

$$\eta = (1 - \pi) \eta_0 \quad (20)$$

and so, the relationship of γ_{cc} to the climate damage function π becomes

$$160 \quad \gamma_{cc} = \pi \eta_0. \quad (21)$$

Moreover, it follows from Eq. 20 that

$$\frac{d \ln \eta}{dt} = \frac{d \ln \eta_0}{dt} - \frac{\dot{\pi}}{(1 - \pi)}, \quad (22)$$

where $\dot{\pi}$ represents the time derivative of the damage function. Inserting this into Eq. 16 then gives

$$i = \frac{d \ln \beta}{dt} - \frac{d \ln \eta_0}{dt} + \frac{\dot{\pi}}{(1 - \pi)} = i_0 + i_{cc}, \quad (23)$$

165 where

$$i_0 = \frac{d \ln \beta}{dt} - \frac{d \ln \eta_0}{dt} \quad (24)$$

is a baseline inflation and

$$i_{cc} = \frac{\dot{\pi}}{1 - \pi} \quad (25)$$

is the contribution of climate damages to inflation. Using the functional form for damages in Eq. 4, this reduces to

$$170 \quad i_{cc} = \frac{1}{1 - \pi} \frac{2\bar{\varphi} \Delta T}{(1 + \bar{\varphi} \Delta T^2)^2} \frac{d \Delta T}{dt} = \frac{2\bar{\varphi} \Delta T}{1 + \bar{\varphi} \Delta T^2} r \quad (26)$$



where $r = d\Delta T/dt$ is the warming rate.

Observe that Eqs. 25 and 26 follow from: (i) the introduction of the aggregate quantity W in Eq. 6, (ii) the functional definition of inflation and the climate damages in Eq. 15 and Eq. 3, and (iii) the assumption of no impact of climate to the nominal production efficiency β , namely that the extra inflation directly caused by climate damage is limited to the real economy, as implicit in the definition in Eq. 17.

We now use Eq. 26 to estimate the implied magnitude of the global inflation increase caused by climate change using estimates for climate damages found in the literature and report the results in Table 1. For each source in the literature (first column), we map the quoted damage π^* at a hypothetical temperature anomaly ΔT^* (second column) into the corresponding parameter $\bar{\varphi}$ (third column) in Eq. 4 through

$$\bar{\varphi} = \frac{\pi^*}{(\Delta T^*)^2(1 - \pi^*)}. \quad (27)$$

We then use Eq. 4 with this calibrated value of $\bar{\varphi}$ and the value $\Delta T(2024) = 1.55^\circ\text{C}$ for the 2024 temperature anomaly since 1850 (Bevacqua et al., 2025) to obtain the implied damage $\pi(1.55^\circ\text{C})$ at current temperature anomaly (fourth column). This in turn allows us to obtain current inflation caused by climate change $i_{cc}(2024)$ (fifth column) from Eq. 26 using the fact that the warming rate since 2010 has been $r = 0.27^\circ\text{C}$ per decade (Hansen et al., 2023). As we can see, today's climate-damage increment to world inflation plausibly ranges from 0.02 to 0.1 % per year across published estimates for climate damages.

Over an additional $+1^\circ\text{C}$ of warming, which at current warming rates would be achieved in 37 years, the implied *cumulative* price-level increase can be obtained as

$$\prod_{t=t_0}^{t_{36}} (1 + i_{cc}(t)), \quad t_0 = 2024, t_1 = 2025, \dots \quad (28)$$

and ranges, approximately, from 1% to 5% (sixth column), or equivalently from 0.03% to 0.13% per year spread evenly over the 37-year increment (last column).

Table 1. Implied inflation cause by climate change for different estimates of damages provided in the literature.

Source	$\pi^* @ \Delta T^*$	$\bar{\varphi} [^\circ\text{C}^{-2}]$	$\pi(1.55^\circ\text{C})$	$i_{cc}(2024) [\%/yr]$	Cum. $+1^\circ\text{C} [\%]$	Avg $[\%/yr]$
Nordhaus (2017)	2.1% @ 3°C	0.00238	0.57%	0.020	0.96	0.026
Barrage and Nordhaus (2024)	3.12% @ 3°C	0.00358	0.85%	0.030	1.44	0.039
Waidelich et al. (2024)	10% @ 3°C	0.01235	2.88%	0.100	4.88	0.130

Observe further that, as a function of ΔT , the climate-induced inflation in Eq 26 attains a maximum at $\Delta T^{\text{critical}} = 1/\sqrt{\bar{\varphi}}$, at which point it equals

$$i_{cc}^{\text{max}} = r\sqrt{\bar{\varphi}} \quad (29)$$

Fig. 1 shows timelines of inflation for the three scenarios considered in Table 1. Taking the assumed value of $r = 0.027^\circ\text{C}/yr$ and a range of values of $\bar{\varphi}$ from Table 1, then i_{cc}^{max} ranges from 0.13% (in the case of Nordhaus (2017)) to 0.30 % per year (in

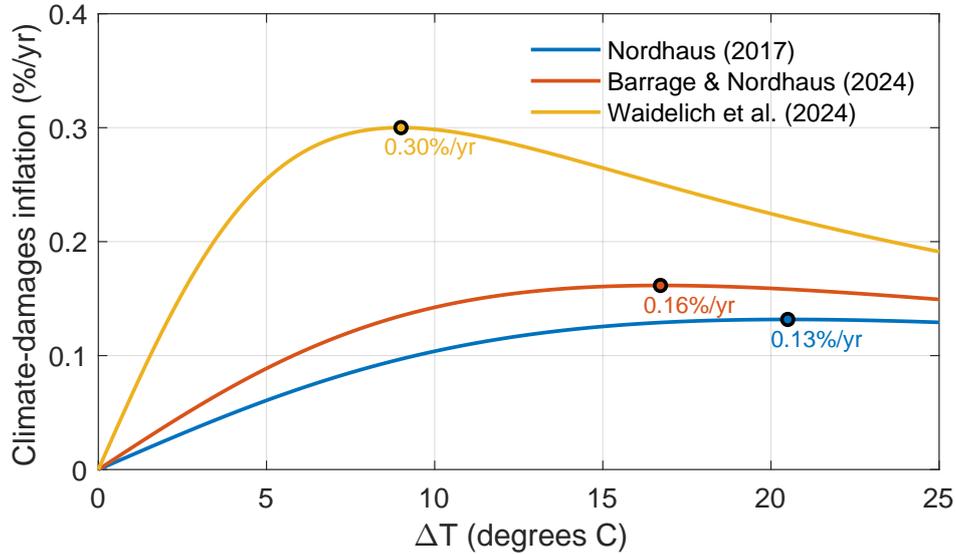


Figure 1. Timeline of future inflation rates i_{cc} adopting the damage functions listed in Table 1. Circles denote $i_{cc}^{\max} = r\sqrt{\bar{\varphi}}$.

the case of Waidelich et al. (2024)), corresponding to extreme warming levels $\Delta T^{\text{critical}}$ at that point ranging from 9.0°C to 4.13°C.

So, even with considerable uncertainty regarding the appropriate value for $\bar{\varphi}$, not to mention the appropriate functional form for π , Eq. 26 makes clear that warming corresponds with higher prices. However, even for the maximum level of rise, added inflation will remain constrained to well less than 1% per year. Note, however, that the inflation curves derive from the smooth, quadratic damage function π for an assumed constant warming rate r and a fixed sensitivity $\bar{\varphi}$. They therefore represent the incremental inflation that would arise if climate damages evolved sufficiently gradually that all macroeconomic quantities instantaneously adjusted, and as such can be interpreted as a conservative estimate. More realistically, both $\bar{\varphi}$ and r are unlikely to remain constant. At high warming levels, feedbacks can steepen damages and accelerate warming (Keen et al., 2022). Once most of the economy is already wrecked in the smooth sense, further warming has a diminished impact. Higher inflation would come from other, more violent mechanisms that the smooth variations are not designed to capture.

Moreover, it follows from Eq. 24 that there is an additional inflationary term $d\ln\beta/dt$ that might rise if governments respond to climate damages by increasing nominal output efficiency β as real output declines. Historical evidence from past climate shocks, such as the Little Ice Age (Zhang et al., 2007), shows price responses an order of magnitude larger pointing to an inflationary sensitivity that becomes highly nonlinear. Accordingly, results for $i_{cc}^{\max} = r\sqrt{\bar{\varphi}}$ could be interpreted as a lower limit for a world that has warmed by +4°C or more.

Purely mathematically, damages could also be switched to the supply side, reducing β rather than increasing γ . Then, i_{cc} would be much smaller by a factor of roughly β_0/γ_0 . As is shown in what follows, β is roughly 30 times larger than γ , and so any change in β in Eq. 15 nearly tracks the change in $\eta = \beta - \gamma$. From inspection of Eq. 24, it follows that shifting all



climate damages to β rather than γ (as we have done in 18), leads to the smallest possible calculated value of inflation caused by climate change. This is because β and η are damaged at nearly the same rate.

It could also be that high warming corresponds to the surprisingly low prediction of inflation increments in Figure 1 because even the high-end values of $\bar{\varphi}$ in Table 1 are too small. Supposing i_{cc}^{\max} were specified then $\bar{\varphi} \simeq (i_{cc}^{\max}/r)^2$. However, maximum
 215 (but still relatively modest) increased inflation rates of say 10% per year would then imply $\bar{\varphi} \simeq 13.7\text{K}^{-2}$, many orders of magnitude larger than the literature values identified in Table 1.

4 A thermodynamic interpretation of inflation

As we have seen, using history as a guide, the empirical literature on natural disasters suggests that climate change should lead to substantial price shocks. On the other hand, calculations based on the damage functions employed in IAMs point to
 220 very low impacts. This disconnect is now explored more deeply by considering the physical forces driving economic growth and decline. To do this, we draw from datasets for economic and energy consumption variables, including W , as outlined by Garrett et al. (2022) for a 50-year time period 1970 to 2019.

We have shown in the previous sections that introducing the term W rather than the standard quantity K as a metric for global value leads to a simple expression for economic inflation. An added motivation for its consideration is that W scales
 225 with world primary energy consumption rates E through an empirically derived near-constant of (Garrett et al., 2022)

$$\bar{w} = W/E = 5.50 \pm 0.21 \text{ trillion 2019-USD per EJ.} \quad (30)$$

namely, there are 5.50 ± 0.21 trillion 2019-US dollars of global historically cumulative wealth supported by each exajoule of energy that is consumed each year. This near-constant relationship was first identified in 2011 (Garrett, 2011), and updated in
 230 Garrett et al. (2022) to show that it has held for a period of 50 years between 1970 and 2019 during which energy consumption increased by a factor of 2.8. Whereas 50 years may seem short compared to the breadth of civilization development, it spans a period encompassing nearly two thirds of growth in civilization's power needs.

A linear *scaling* in Eq. 30 is fundamentally different from the linear *correlation* often noted for Y and E (Cleveland et al., 1984). The 2.8 factor increase in E was associated with a factor of 4.5 increase in Y . Certainly Y and E can be statistically correlated. Indeed the coefficient of determination is $R^2 = 0.98$. However, the ratio Y/E steadily increased by 57%, meaning
 235 that there is no linear scaling as the word is mathematically defined. Meanwhile wealth W increased nearly equally rapidly as E , by a factor of 2.7, so the ratio $w = W/E$ remained stable. In terms of a production relation, Eqs. 6 and 30, understood to mean that \bar{w} is a constant, imply

$$Y = \bar{w} \frac{dE}{dt} \quad (31)$$

and from Eq. 7:

$$240 \quad Y_N = \bar{w} \left(\frac{dE}{dt} + \gamma E \right) \quad (32)$$



Real production requires expansion of the power supply, expressed as a positive rate of change for E . Nominal production depends additionally on E itself in proportion to the decay rate γ . In other words, real production can collapse even as nominal production continues, for example if E is constant.

Thus, civilization Wealth W is not only a convenient mathematical construct for obtaining a simplified interpretation of inflation within the global economy, but it is also empirically tethered to the observable quantity of the rate at which civilization dissipates power in the form of primary energy. For greater physical intuition, the global economy could be imagined as an array of networks that has been slowly built up over time through real production, each increment in network size requiring added energy to sustain. To draw another analogy, a deciduous tree can be reasonably divided into its components of leaves, exterior sapwood and interior heartwood (Shinozaki et al., 1964; Oohata and Shinozaki, 1979). Leaves are the primary energy providers that fuel the tree through photosynthesis, driving fluid circulations through the sapwood. Each year, the leaves die, leaving new sapwood that becomes an “investment” in heartwood at the center of the tree. Formed cumulatively over many years, the heartwood structurally supports a larger more consumptive tree. Heartwood may no longer operate as an active part of the tree’s “economy” in the current year, but if it did not exist, the more economically active sapwood would collapse. Indeed, it is only with the accumulation of past heartwood – the tree’s “wealth” – that sapwood can be sustained.

By extension, the whole of civilization may be viewed as a “superorganism” (Gowdy and Krall, 2013) that, like the tree, built up over its history the current networks that power through energy consumption circulations along it. And so, any new network building leads to greater future energy demands. Economically, “consumption” of our hypothetical sandwich has an effect on civilization that goes beyond simple sustenance. It also helps to develop sublime memories, encoded by building new neural networks, of the combination of butter, ham and a freshly baked baguette. Consumption spurs future demand for a greater form of sustenance than mere bread. The value then lies not so much in the sandwich itself, but instead within its relationship to its surroundings, specifically people, and how the sandwich fuels us to productively engage in the world around us. As another example, gold coins have a clear value as part of a financial system, but none if they are lost in the desert. It is only through relationships, or networks, that new value can be created. By extension to a more global perspective, previously constructed economic structures that include people, their knowledge, roads, building and telecommunications networks, and everything else of what constitutes humanity as a historically accumulated whole, fuel its current primary energy needs.

There is the component of matter, too. Networks are constructed in the past from matter mined from reserves. In the present, they enable dissipation of energy to move matter around the networks. Only in the case that more energy is available than needed for these circulations can new networks can be constructed. The implication of \bar{w} being a constant is that we can express civilization’s size either in units of physical power, or in units of inflation-adjusted currency, and that the growth rates of both should be nearly equal. From Eqs. 12 and 30.

$$\eta_E = \frac{d \ln E}{dt} = \eta \quad (33)$$

As anticipated, the mean value of η_E for the years 2000 and 2019 was 0.0205 yr^{-1} , very similar to the aforementioned value of 0.0227 yr^{-1} for η .



With a scaling tying W to E , it becomes possible to interpret economic inflation in more physical terms, including how it is potentially affected by climate damages (Garrett, 2014). Consider the totality of civilization as a complex array of networks that dissipate primary energy as heat at rate E . Generally, diffusive flows are in proportion to some characteristic constant rate coefficient $\bar{\kappa}$ and a potential gradient ΔG . Here, ΔG would represent the potential for civilization networks to dissipate primary energy, the potential difference being that between the availability to civilization of the energy in the primary energy supply and the (zero) availability of the waste heat that eventually radiates to space. That is to say, we postulate that

$$E = \bar{\kappa}\Delta G \quad (34)$$

Thus, from Eq. 30, it follows that civilization's cumulative Wealth effectively represents a thermodynamic potential, one that is evaluated relative to an "uncivilized" environment. Then, from Eq. 34:

$$W = \bar{w}\bar{\kappa}\Delta G \quad (35)$$

The potential gradient ΔG can be further divided into a number of elements n . The number of elements might be the number of human individuals globally, but it could just as easily be anything we think of as defining civilization, perhaps most abstractly a civilization network "node". However civilization nodes are defined, there is a mean potential gradient per node $\Delta\mu$, so that $\Delta G = n\Delta\mu$ and

$$\frac{d\Delta G}{dt} = n\frac{d\Delta\mu}{dt} + \Delta\mu\frac{dn}{dt} \quad (36)$$

Rome was not built in a day: just as W is an expression of cumulative inflation-adjusted economic production, the potential energy ΔG represents the historic culmination of civilization's thermodynamic work, work that has cumulatively "lifted" civilization to an ever higher potential than its "uncivilized" environment. With work, the matter in Earth's crust is transformed through a "phase change" into the stuff of civilization, one with more nodes and more circulatory energy per node (Garrett et al., 2020). In terms of growth rates, from Eqs. 33 and 34 one obtains

$$\eta_E = \frac{d\ln \Delta G}{dt} = \frac{d\ln n}{dt} + \frac{d\ln \Delta\mu}{dt} = \eta_n + \eta_{\Delta\mu} \quad (37)$$

That is, growth in energy consumption is available to be partitioned among material and energetic growth at respective rates η_n and $\eta_{\Delta\mu}$.

Just as civilization uses energy reserves to do work to grow itself, the environment does work on civilization to cause its decay. The number of civilization nodes, and the potential per node, can only increase provided it can overcome this environmental "drag". Substituting Eq. 35 into Eq. 10:

$$\frac{d\Delta G}{dt} = \beta\Delta G - \gamma\Delta G = \eta\Delta G \quad (38)$$

Work done to grow civilization's potential by transforming the Earth's crust at rate $\beta\Delta G$ is offset by the drag on civilization growth due to decay at rate $\gamma\Delta G$, with the net rate of work being $\eta\Delta G$. If drag outweighs the forces for growth, then civilization shrinks as $\eta = \beta - \gamma < 0$, with ΔG – the thermodynamic distinction between civilization and its uncivilized environment –



305 fading along with economic wealth W , including declining population and per capita wealth, which history shows is also often associated with inflation.

To get a sense of the magnitude of these thermodynamic quantities, we can reasonably assume that $\bar{\kappa}$ is an inverse day because our most typical routines are daily (Garrett et al., 2020). Then, taking the 2019 value for E of 595 ExaJoules (Garrett et al., 2022), the 2019 value of ΔG is 1.6 ExaJoules or 260 million barrels of oil equivalent. Adopting population as representative of the number of civilization elements, that is $n = 7.7$ billion, the 2019 potential per capita $\Delta\mu$ is 210 MegaJoules or 5.2
310 liters of oil equivalent, a potential that must be sustained daily against dissipation at the per capita rate of 2.4 kW or 5.8 liters of oil equivalent per day. The mean growth in energy consumption averaged over the period 1970 to 2019 (Garrett et al., 2022) is $\eta_E = 2.17\% \text{ yr}^{-1}$, which can be partitioned between population n and per capita potential $\Delta\mu$. The observed growth rate in population is $1.52\% \text{ yr}^{-1}$, which leaves as the energetic residual according to Eq. 37 a growth rate for $\Delta\mu$ of $0.65\% \text{ yr}^{-1}$.

Estimates of β and γ can be related to inflation statistics. Defining the relative difference, or wedge, between nominal and
315 real output by

$$J = \frac{\gamma}{\beta} = \frac{Y_N - Y}{Y_N}, \quad (39)$$

we can see that this is related to inflation, which we previously defined formally as the growth rate of the ratio Y_N/Y . More precisely, using the fact that $\eta = \beta - \gamma = \beta(1 - J)$, it follows from Eq. 15 that

$$i = \frac{d\ln(\beta/\eta)}{dt} = \frac{\dot{J}}{1 - J} \quad (40)$$

320 Rearranging the terms in Eq. 39, we find that

$$\beta = \frac{\eta}{1 - J} \quad \gamma = \frac{J}{1 - J}\eta. \quad (41)$$

Averaged over the period 1970 to 2019 (Garrett et al., 2022), we have that $\eta \simeq 0.0205 \text{ yr}^{-1}$ (2.05% per year) and $J \simeq 0.036 \text{ yr}^{-1}$ (3.6% per year). Then, from Eq. 41, we obtain that $\gamma = 0.00076 \text{ yr}^{-1}$ (0.076% per year) and $\beta = \eta + \gamma \simeq 0.021 \text{ yr}^{-1}$ (2.1% per year). Note that in the low-inflation limit $\gamma \simeq \eta J$.

325 A value of γ corresponding to a halving time from decay of Wealth of approximately 910 years might seem extraordinarily slow. It is especially remarkable in contrast with the decay rate for capital K , which is usually taken to be two orders of magnitude higher, or a few percent per year. Perhaps it speaks to the arguments we make that the “heartwood” of civilization’s history does indeed have a very long arm, much longer than the “sapwood” currently valued as marketable capital today. The driving force for growth β may be ready access to the mineral and energy resources that are required to lift civilization’s
330 potential today. Real growth at rate η appears resistant to rapid environmental decay at rate γ perhaps because our core cultural history, which can include our literary and scientific knowledge, is surprisingly insulated from environmental decay.

That is to say, a low value of γ may be viewed optimistically as an indication that society is highly resilient to any accelerating damages from climate change – the historical arc of civilization has been long enough to that long-standing elements like our language and culture provide a buffer: whatever happens in the future, civilization’s core – it’s heartwood – will remain mostly
335 intact. Nonetheless, climate change will surely require a redirection of resources from growth to repair in order to maintain real



productivity. As Eq. 18 suggests, there is no guarantee that γ will stay low. We will still do thermodynamic work to transform the Earth's crust into civilization networks in an effort to sustain growth. But if γ grows enough, even if β stays stable, then eventually ΔG will cease to grow at a positive rate η_E . Instead, as γ increases to the point that $\gamma > \beta$, growth will turn negative with $\eta_E < 0$.

340 The trajectory of civilizations throughout history is to sequentially transition from explosive super-exponential growth to exponential growth to sub-exponential growth to stagnation, to collapse (Ausubel, 2007; Garrett, 2015), so a transition from consumptive growth to collapse with $\eta_E < 0$ is certainly possible, if not expected. By analogy to the tree, climate damages may first prune the leaves and twigs, then burrow into the sapwood and ultimately rot the heartwood. As the tree sickens, its energy consumption declines. As climate damages increase the value of γ , the gap between the nominal and real GDP will widen, and
345 inflation will necessarily rise.

5 Is global hyperinflation possible with climate change?

Eq. 33 indicates that the growth rate of historically cumulative wealth matches its growth rate of energy use. Empirically, the combination of $d \ln W / dt = \eta$ and the observed scaling $W = \bar{w} E$ implies $d \ln E / dt = \eta_E = \eta$. At the point when world energy consumption stagnates, that is $\eta_E \equiv \eta \rightarrow 0$, Eq. 10 implies that $\beta \rightarrow \gamma$. The limit of η (or η_E) approaching zero does
350 not mean that nominal production ceases, rather that net real additions to cumulative wealth vanish because $Y_N = \gamma W$. In this steady-state, all work and nominal flows are directed to maintenance of existing infrastructure so that $d \Delta G / dt \rightarrow 0$, with no further growth. With stagnation, the inflation identity $i = d \ln(\beta / \eta) / dt$ in Eq. 15 becomes ill-defined: inflation blows up, and "real" production becomes impossible to accurately measure, even though energy and material resources continue to circulate because ΔG remains positive (Eq. 34). It is not that real production Y halts as $\eta \rightarrow 0$, but instead that it loses meaning as price
355 levels sky-rocket.

From the standpoint of Eq. 40, as $J \rightarrow 1$ (i.e. $\eta = \beta - \gamma \rightarrow 0$), it follows that even for the case of a small $\dot{J} > 0$, climate damages could still lead to very high inflation. Optimistically, the efficiency of nominal production β could be unaffected by climate change and stay flat. Nonetheless, if mounting decay and maintenance burdens from climate change cause η to fall from its current rate of near 2% to 0.2% over a decade, then (assuming constant β), $i \simeq -\Delta \ln \eta / \Delta t \simeq \ln(0.02/0.002)/10 \simeq$
360 0.23 yr^{-1} (or 23%/yr). Taking a mean value for η of 0.01 yr^{-1} – that is energy consumption is still growing over the period but at a reduced rate of roughly one percent per year – then from Eq. 13, GDP growth drops to -0.22 yr^{-1} (negative 22% per year). Hyper-inflation goes hand-in-hand with a phase of collapse in economic production.

Figure 2 turns the problem on its head to ask how fast $J = \gamma / \beta$ would need to grow for inflation to become unstable such that Eq. 40 explodes with $\gamma \rightarrow \beta$. (For the sake of calculations, it does not matter whether $J \rightarrow 1$ because γ increases or β
365 decreases, or some combination of the two.) We find that instability with hyper-inflation can arrive quite quickly. Even if J increases by just 0.1% per year from recent values, inflation explodes in the 2060s, and at 10% per year it explodes in the 2030s. The real economy fails slowly and then suddenly, dying a "death by a thousand cuts". Damages may be survivable at

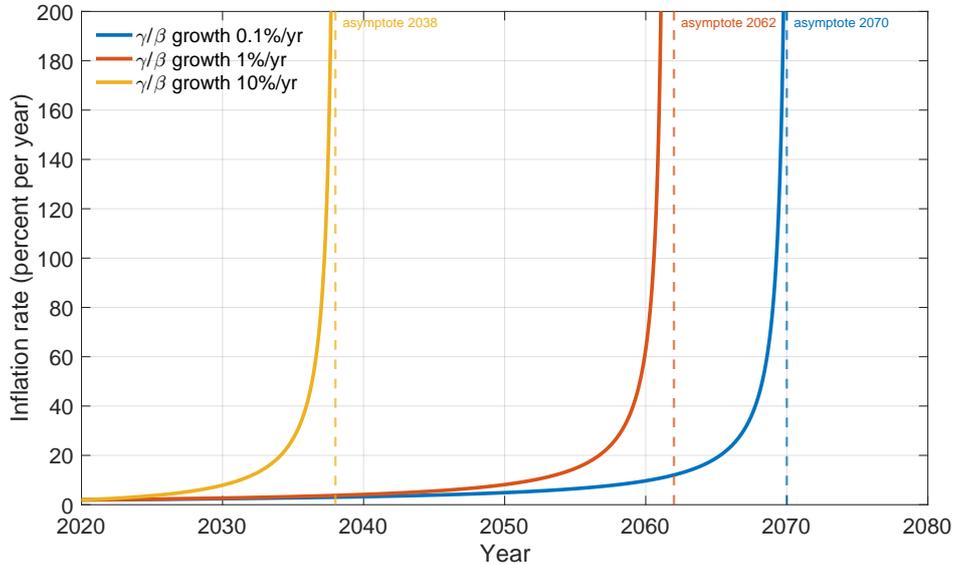


Figure 2. Timeline of future inflation rates assuming varying rates for the increase in the decay rate γ , that is $d\ln\gamma/dt$, and assuming a constant value of β . Trajectories are initialized to a mean inflation rate for the period 2000 to 2019 of $i = 1.94$ %/yr, $\gamma = 0.05$ %/yr, and $\beta = 2.4$ %/yr.

first because $\beta \gg \gamma$, but with time, the singularity of $\beta \simeq \gamma$ is approached as nominal production becomes nearly overwhelmed by decay.

370 6 Conclusions

In this paper, we find that widely-used climate damage functions do not lead to significant inflation, but that very high inflation cannot be ruled out. To arrive at this conclusion, we developed a minimalist framework that establishes inflation as an intrinsic property of the global economy. Central to this framework is a mathematical quantity we term Wealth W , defined as the time integral of past real production Y such that $W = \int_0^t Y(u) du$. With $\eta = Y/W$ and $\beta = Y_N/W$ being the real and nominal production efficiencies of W , we have that $\eta = \beta - \gamma$ where γ is the decay rate of W . This leads to a new compact expression for inflation $i = \dot{J}/(1 - J)$ where $J \equiv \gamma/\beta$. Inflation is therefore not exogenous. Rather, it can be related to a combination of accelerating decay of previously accumulated infrastructure and declining efficiency of nominal production.

Assuming that climate damages to the real GDP π initially affect the decay rate γ leaving β approximately constant, the climate–damage increment to inflation becomes $i_{cc} = \dot{\pi}/(1 - \pi)$. Adopting literature values of the damage sensitivity $\bar{\varphi}$ and recent warming rates, this “smooth”, slowly-varying component of inflation is bounded by $i_{cc}^{\max} = r\sqrt{\bar{\varphi}}$ and amounts to an increment of no more than 0.3% per year, even for high damage sensitivities and extremely high levels of warming.

However, this very small contribution of climate damages to inflation does not allow for inflationary shocks driven by an ongoing increase in climate driven decay. There is an empirical relationship grounding W through a constant scaling factor \bar{w}



to the global primary energy consumption rate E . Accordingly, long-run inflation-adjusted GDP growth can be expressed in
385 terms of a single efficiency parameter $\eta = d \ln W / dt = d \ln E / dt$. A scenario in which climate damages, resource depletion,
and other shocks increase the decay rate γ , or decrease β , can push the growth rate of energy use $\eta = d \ln E / dt$ toward zero,
 $J = \gamma / \beta \rightarrow 1$, and consequently $i \rightarrow \infty$. In other words, all nominal output is absorbed by the maintenance and replacement
of previously produced civilization networks, and inflation rates explode.

So, within the narrow confines of smoothly adjusting IAMs, climate change appears to have at most a very modest impact on
390 global inflation. However, once climate damages and other stresses cause decay rates to rise high enough that energy use stalls,
inflation and real output become tightly coupled, and stagflation and hyperinflation emerge during the transition from a phase
of growth to one of collapse. Our results provide a theoretical basis for interpreting historical episodes where environmental
shocks coincided with both output decline and price instability. Looking forward, it will become important to track not only
damages to real GDP, but also a potentially growing gap between nominal and real flows as evidence of accelerating decay. If
395 decay accelerates as anticipated, policy measures that stabilize energy use, emissions, and GDP growth in real terms may still
be inflationary. Future work could extend this framework to include explicit impacts on monetary institutions, and the potential
for alternatively formulated damage functions to better capture climate-driven instabilities in the economic system.



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