Discussion phase response to Reviewers

We thank the three reviewers for their careful reading of the manuscript and for raising several points that help us clarify the intended scope and contribution of the manuscript. We agree that the impacts of climate change on prices and inflation are less developed than the impacts on real output. This gap is precisely the motivation for the paper.

The reviews appear to evaluate the manuscript mainly against the expectations of a conventional monetary or regional price-level models for inflation. Our manuscript has a different aim. We introduce a deliberately highly aggregated global framework in which inflation emerges from the widening gap between nominal and real production, with real production defined in terms of inflation-adjusted output and its historical accumulation into the quantity we call Wealth. The core definition is $W(t) = \int_0^t Y(u)\,du$ *where* Y *is real, inflation-adjusted global output. The manuscript then examines the consequences of writing nominal output as* $Y_N = \beta W$*, decay of historically accumulated Wealth as* γW*, and real output as* $Y = (\beta - \gamma)W$*. This construction is central to the paper and is distinct from standard monetary models of regional price determination.*

We will revise the manuscript to make this scope clearer, to better distinguish our approach from monetary theories of inflation, to clarify concerns about units comparing real and nominal GDP, to simplify some of the mathematics for readability in the abstract, and to explain more explicitly why long-run inflation is relevant in the context of climate damages, investment, and the interpretation of IAM results.

1. *The title will be changed to* Climate change, economic decay, and the risk of global inflation

2. *For readability that reduces the number of equations, the abstract will be changed to:* Regional climate anomalies have historically been associated, in turn, with price increases, social conflict, and economic decline. Integrated Assessment Models (IAMs) used to estimate future climate damages, however, generally describe losses to real, inflation-adjusted GDP, while offering little guidance on the inflationary response. Here, we introduce a highly aggregated framework for world economic growth in which inflation is treated as an intrinsic property rather than an exogenous forcing. The framework builds from the definition of a new quantity termed civilization "Wealth" as the historical accumulation of global real output. Over an accounting interval, normally one year, nominal production is decomposed into a real addition to Wealth and a period-averaged decay or devaluation term. Inflation then reflects a changing gap between nominal production and real additions to Wealth. We show that standard IAM climate damage formulations translate into faster decay of Wealth, but that, even for high-end damage estimates and global mean temperature increases, the annual inflation increment remains small, less than about 0.3% per year. Nevertheless, larger global inflationary shocks cannot be ruled out. Empirically, Wealth is linked to global primary energy consumption through a constant scaling factor. If climate change or other stresses accelerate decay so that production is redirected from expansion toward maintenance, then the growth of energy use and Wealth could slow towards stagnation. In this limit, the gap between nominal and real production widens rapidly, and stagflation or even hyperinflation emerge as key signatures of global economic distress. These results suggest that assessments of climate damages should track not only damages to real GDP, but also the risk for a widening gap between nominal activity and real accumulation.

3. *The introduction will add the text* 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 global-scale climate-damage function π. The new framework we introduce is not intended to substitute for monetary, fiscal, or regional theories of price-level determination, or address the important problem of the impact of weather extremes on, e.g., the price of food, energy, housing, insurance, goods, and transport. Nor does it address how the inflationary consequences of climate shocks depend on both supply and demand on more regional and sectoral scales.

   Instead, our focus is more aggregated, aimed at addressing the limiting global case of how climate damages and other economic stressors drive inflation. We accomplish this by moving beyond the traditional neoclassical economic framework to introduce a highly aggregated mathematical identity, analogous to but much more extensive than 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 increase due to accelerating decay of previously produced social and built infrastructure, with a consequent erosion of our collective capacity to access energy supplies. Although existing climate damage scenarios do not allow for very high inflation in the future, even for particularly elevated values of π, we show that stagflation and even hyperinflation may nevertheless emerge, because decay increasingly redirects global nominal production away from growth and towards maintenance of what was previously produced.

4. *Section 2 is extensively rewritten to better relate the material to standard economics approaches and to clarify a concern that there is an inconsistency with units:*

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 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 millenia ago of the number system and 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, leads to definition of a cumulative quantity W previously termed "Wealth" in Garrett (2011, 2014), for which the dynamic equation is:

$$\frac{dW}{dt} = Y \tag{1}$$

The integral form of Eq. 1 is the accumulation over history of prior real global economic output $Y(u)$ for $u \in [0, t]$:

$$W(t) = \int_0^t Y(u)du \tag{2}$$

By contrast with the equation for capital, Wealth in Eq. 1 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". Thus, the reason for introducing Wealth is to acknowledge how current global production depends on all components of the current economy but also historically accumulated civilization networks that include – for example – physical infrastructure, energy systems, institutions, knowledge, education, law, language, and financial instruments. In this sense, Wealth is far broader in scope than produced capital K as represented in a Cobb-Douglas production function.

Whatever its significance, at this stage in the development, Eq. 2 remains merely a mathematical identity. Economically, it might seem to lack meaning because, at a minimum, it appears to lack the necessary sink term of depreciation that is explicit in the standard dynamic equation for capital. However, a sink term becomes more apparent once we consider the difference between the continuous variables of nominal output Y_N and real output Y. Quantitative assessments of Y_N include both a real component associated with economic output expressed in fixed-year currency, e.g. 2019, and a price component associated with how that output is valued in the current year. For this, observe that we can restate Eq. 1 as:

$$\frac{dW}{dt} = Y_N - \gamma W \tag{3}$$

It is important to reiterate that Wealth is defined only as the historical integral of real, inflation-adjusted output as in Eq. 2.

Eq. 3 raises a possible concern that a real quantity γW with fixed year currency is being subtracted from a nominal quantity with variable year currency to calculate changes in W. To address this issue, we note that nominal and real GDP are normally related through a GDP deflator p with units of current dollars per real reference dollar such that, if $Y_N^\$$ is the nominal GDP for any given year then, [1],

$$Y = \frac{Y_N^\$}{p}. \tag{4}$$

What is done in Eq. 3 is to define $\mathcal{U}$ as a unit-alignment factor with numerical value one and units of real reference dollars per current dollar so that

$$Y_N \equiv \mathcal{U} Y_N^\$ \tag{5}$$

in which case Y_N has the same units as Y and dW/dt, while retaining the numerical value of nominal GDP $Y_N^\$$. Then we can define $P = \mathcal{U}p = Y_N/Y$ as a dimensionless price factor relating the current year to the assigned fixed year so that,

$$\gamma W = Y_N - Y = (P-1)Y \tag{6}$$

or, dividing by W,

$$\gamma = \frac{Y_N - Y}{W} = (P-1)\frac{Y}{W}. \tag{7}$$

Operationally, the value of γ can be calculated from the definition of inflation

$$i = \frac{d\ln P}{dt} = \frac{d\ln(Y_N/Y)}{dt}, \tag{8}$$

in a semi-continuous sense. Observed time series for the global nominal and real GDP series are tallied annually. From these statistics, the inflation rate can be calculated as a finite-difference approximation to $d\ln P/dt$ given by Eq. 8. For an accounting interval Δt, normally one year, this gives a local gross inflation factor $\Pi = \exp(i\Delta t)$. The unit-aligned nominal valuation Y_N used in Eq. 3 is then calculated as $Y_N^\Delta = \Pi Y$, in which case the interval-averaged decay or devaluation coefficient γ becomes

$$\bar{\gamma} = \frac{Y_N^\Delta - Y}{W} = (\Pi - 1)\,\frac{Y}{W}. \tag{9}$$

Thus, γ is calculated from the local year-to-year rate at which the nominal-to-real valuation ratio changes assigning $\gamma = \bar{\gamma}$.

For positive inflation over a chosen accounting interval – usually a year – where $Y_N > Y$, then the term $\gamma W > 0$ provides the desired mathematical sink term in the accumulation of W. Purely from an economic accounting perspective, γ represents the rate at which the unit-aligned nominal valuation of current production must be corrected within a given time interval so that the accumulation of Wealth dW/dt can remain evaluated in real terms. All instantaneous nominal output in the current year and all prior years is “saved” (namely, analogous to $s = 1$), but its net addition is offset by a revaluation of Wealth at fractional rate γ.

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[1] Here “chain-aggregated real units” are used to construct the real GDP so that adjacent-year changes in production are linked into a single index and then normalized to a reference year, so that Y can be expressed in every year for the purpose of comparison or addition, in such units as chained 2019 dollars (Blanchard, 2017). Through chain-aggregation it is possible to remove the effects of changing prices on current-dollar valuations to isolate changing real production.

Adding some mathematical sophistication, one could consider that the full breadth of civilization elements constituting Wealth as each losing value with its own characteristic time τ so that there is a spectrum of revaluation rates $\gamma(\tau)$. Then, γ in Eq. 3 can be reexpressed as

$$\gamma = \frac{1}{W}\int_{t_0}^{\infty} \gamma_W(\tau)\, W(\tau)\, d\tau \tag{10}$$

where $W(\tau)$ is the amount of Wealth with remaining lifetime τ. As extreme examples, the spectral decay or devaluation rate γ_W approaches zero for such long-lived bedrocks of humanity as the alphabet, and it becomes very large for a sandwich. In effect, γ represents the instantaneous revaluation rate of all that was previously produced, was previously reevaluated, and is still losing value now.

Eqs. 1 and 3 can now be reexpressed as

$$\frac{dW}{dt} = \beta W - \gamma W = \eta W \tag{11}$$

where:

$$\eta = \beta - \gamma, \quad \beta = \frac{Y_N}{W}, \quad \eta = \frac{Y}{W} \tag{12}$$

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 availability. Thus, $\eta = \beta - \gamma$ is the net output efficiency, in some ways similar to the total factor productivity A in Eq. **??** 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 the Cobb-Douglas formulation, namely of inverse time.

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 a sink term, 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 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. The term Wealth is therefore not used here in the conventional sense of a marketable asset stock or net worth as applies to capital K. Our interpretation is that instead it is a cumulative state variable for civilization, measuring the historical accumulation of real production that has contributed, directly or indirectly, to the present organization of the global economy. *Past* consumption contributes to W only insofar as it has helped construct, maintain, educate, organize, or otherwise sustain the networks from which *current* production Y arises. Eq. 3 then introduces the offsetting revaluation or decay term required to distinguish this cumulative history from the real addition that remains after maintenance and replacement.

So, there are four important mathematical benefits of using Wealth W over capital K to study civilization evolution. First, the dynamic Eq. 3 is simple, requiring no assumptions about savings or depreciation rates. Second, 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 third is a simplified treatment of GDP growth. Note how from Eq. 11, the instantaneous rate of exponential growth for Wealth is:

$$\frac{d\ln W}{dt} = \eta \tag{13}$$

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

$$\frac{d\ln Y}{dt} = \eta + \frac{d\ln\eta}{dt} \tag{14}$$

or the sum of the growth rate of historically cumulative production W and the growth rate in the growth rate – what we previously termed the innovation rate (Garrett, 2015). Instead of it being necessary to consider the time evolution of three variables for calculation of GDP growth as for the Cobb-Douglas production function (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.

A fourth benefit is a ready link between the decay or revaluation rate γ and inflation i. 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 P. Using Eq. 12, we find

$$P = Y_N/Y = \beta/\eta = 1 + \gamma/\eta, \tag{15}$$

from which it follows that:

$$i = \frac{d\ln(\beta/\eta)}{dt} = \frac{d\ln(1+\gamma/\eta)}{dt} \tag{16}$$

or

$$i = \frac{d\ln\beta}{dt} - \frac{d\ln\eta}{dt} \simeq \frac{d}{dt}\left(\frac{\gamma}{\eta}\right) \tag{17}$$

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. 14, 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 may be coupled, what may be termed colloquially as stagflation.

A concern raised by Reviewer 1 that the changing ratio of production to energy is not concerned is addressed with the added text A further important implication of constant $\bar{w}$ can be seen by comparing the equation for η_E with Eq. 14, namely that:

$$\frac{d\ln Y}{dt} = \eta_E + \frac{d\ln\eta}{dt} \tag{18}$$

Long-term growth in global economic output (the left hand side of the equation) is driven not just by growth in energy consumption (the first term on the RHS) but the growth rate of the growth rate (the second term). If the second term is non-zero, then Y and E can become decoupled. Indeed, for the same 2000 to 2019 period the mean global real GDP growth rate was $0.0294\,\mathrm{yr}^{-1}$, a growth rate 43% higher than the energy consumption growth rate. This is because the observed mean value of $d\ln\eta/dt$ was $0.0114\,\mathrm{yr}^{-1}$. So, constant $\bar{w}$ implies observed values for the two sides of the equality agree to within 10%, specifically $0.0294\,\mathrm{yr}^{-1}$ versus $0.0319\,\mathrm{yr}^{-1}$. The implication is that real output may stagnate, even as civilization manages to maintain growing energy consumption with η_E remaining positive – if the growth of civilization is slowing and $d\ln\eta/dt$ turns negative to a similar magnitude.

5. *A discussion about a comparison of the methods described here with more tradiational perspectives on the forces describing inflation is added to Section 5*

In a more smoothly varying model of inflation that assumes frictionless adjustment, as is standard, changes in nominal prices do not necessarily reduce welfare. Our approach differs by addressing how inflationary shocks can be linked to an accelerating redirection of nominal economic activity from net expansion towards maintenance and repair. While this lies beyond the immediate scope of this paper, such a redirection might reasonably be expected to impact such fundamental economic aspects as how wealth is distributed, long-term investments, and the measurement of real growth. Damages to previously constructed networks from climate change, or any other force that constricts economic output, may emerge as rising prices but reflect a deeper underlying problem – a diminishing capacity of civilization to a generate net real addition to its accumulated productive infrastructure. As repair consumes the bulk of new production, inflation sky-rockets.

Our approach does not preclude monetary policy for controlling the short-run timing and magnitude of inflation, especially nationally. Rather what we address are the more fundamental underlying forces such as climate change that act as inflationary pressures over the long-run and at global scales, those that turn a growing share of nominal output towards merely maintaining or replacing previously constructed Wealth. Monetary policy may change how such a pressure is allocated internally, among countries, or between e.g. wages, debts, and the prices of goods. It cannot however erase the physical destruction of previously built networks or reduced access to resources of energy and raw materials. As $J \to 1$, the option available to central banks may become severely constrained, effectively limited to rearranging deck chairs on the Titanic.

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