Greenhouse Gas and Cyclical Growth: A Medium-run Keynesian, Long-run Ricardian Simulation Model

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Key Features I

Almost all models of long-run interactions between economic growth and climate change are built up from a supply-side perspective, assuming full employment of labor and other resources. Moreover, many presume "optimal growth," which diverts attention from real world policy choices.

Here we look at these issues from the angle of aggregate demand in the "medium" run, with emphasis on output and employment adjustment. Economic growth and CO_2 accumulation are both endogenous to the system – one cannot directly control one or the other.

The "long" run is set up as a "steady state" in which demand and supply effects commingle.

Key Features II

Output and capital accumulation are demand-driven in medium run – the Keynesian aspect of the model.

Higher capital per capita increases output which in turn increases the speed of CO_2 accumulation.

Higher atmospheric CO_2 concentration reduces output and growth of capital per capita.

Hence we have a variation on "typical" predator-prey dynamics – CO_2 is the predator and capital per capita the prey. Numerical simulations suggest an upswing in capital per capita for around eight decades, followed by a crash *of output and capital only.*

Key Features III

Contrary to familiar fox-and-rabbit models, the decay rate of CO_2 in the atmosphere is *very* slow (the "fox" is almost immortal). *Concentration remains high*, blocking any chance of economic recovery.

We follow the usual growth theory convention of setting up a model that converges to a steady state.

In practice the system *must* converge to a *stationary* state with constant capital stock, CO_2 concentration, etc. Otherwise, CO_2 accumulation will overwhelm the economy – the Ricardian aspect.

Key Features IV

Investment in mitigation of CO_2 accumulation can offset the crash, and lead to a non-dismal stationary state. In numerical simulations the share of output required is on the order of total world "defense" spending and roughly double worldwide energy consumption subsidies.

Three key relationships determine these results – proper growth accounting for accumulation of capital and CO_2 and a damage function (set up in two ways) indicating how rising CO_2 concentration cuts into capital accumulation, output, and employment.

Model Architecture I

3 dynamic variables: CO_2 concentration in ppmv (G), capital stock per capita (κ), and the output/labor ratio (“labor productivity” ξ).

Increase in G (or $\dot{G}$) is proportional to output (X) with factor of proportionality reduced by outlay on mitigation (m) as share of X.

Increase in κ (or $\dot{\kappa}$)driven by investment/capital ($g = I/K$) less depreciation (rate δ) and population growth rate (n)

Labor productivity growth rate ($\hat{\xi}$) driven by growth rate of “energy intensity” or the energy/labor ratio ($e = E/L$)

Model Architecture II

Ricardian long run: $\dot{G} = \dot{\kappa} = \hat{\xi} = \hat{e} = n = 0$. So G, κ, X, capital stock (K), employment (L) and population (N) are all constant.

Keynesian medium run: X and L determined by effective demand driven by g and m

Medium run "capital utilization" $u = X/K$ *increases* with profit share π ("profit-led") via an increase in investment demand $g(\pi)$ so $u = u(\pi)$.

Model Architecture III

Assume that π *decreases* with $\lambda = L/N$ in a "profit squeeze" à la Marx/Kalecki/Goodwin – this response assures medium-run stability. In one variant π is squeezed by G as CO_2 concentration drives up costs.

In another variant, π decreases just with λ but higher CO_2 concentration raises the depreciation rate ("capital destruction")

Key identity $\lambda = \kappa u/\xi$ means that higher κ increases λ, and reduces π and g. Lower g means that growth of κ slows, i.e. $d\dot{\kappa}/d\kappa < 0$ so growth in capital per capita is (locally) dynamically stable.

Model Architecture IV

An alternative closure would make demand "wage-led," in which case higher G would "naturally" reduce labor share or increase π.

For medium-run stability there would have to be a high employment "wage squeeze." Two problems:

At least at business cycle frequencies a wage squeeze or $\partial\pi/\partial\lambda > 0$ is counter-factual

A higher $g(\pi)$ in response to $\partial\pi/\partial\lambda > 0$ and $\partial\lambda/\partial\kappa > 0$ would make $d\dot{k}/d\kappa > 0$ and growth would be dynamically unstable.

Dynamics I -- CO_2 accumulation

Following the "Kaya identity" from climate science, the accumulation equation for CO_2 is

$$\dot{G} = \chi E - \mu(m)X \ - \omega G = [(\chi/\varepsilon) - \mu(m)]X - \omega G$$

with $\varepsilon = X/E$ as energy productivity. Higher mitigation m reduces factor of proportionality of $\dot{G}$ wrt X. Dissipation parameter ω for G is very small.

There is a steady state at

$$G = \omega^{-1}[\chi(e/\xi) - \mu(m)]uN\kappa = \omega^{-1}[(\chi(e/\xi) - \mu(m)]X$$

Note that steady state G is proportional to steady state u, κ, and N (a Malthusian touch – numbers below) or steady state X.

Dynamics II– Growth of capital stock per capita

Capital stock basically scales the system (there is no aggregate production or cost function although the identity $\lambda = \kappa u/\xi$ and $\partial\pi/\partial\lambda < 0$ do apply).

The other key accumulation equation is for capital per capita

$\dot{\kappa} = \kappa(g - \delta - n)$.

(Recall stability discussion above.)

With $n = 0$ there is a steady state at $g = \delta$.

Higher m shifts up medium run g and steady state κ.

Steady state with profit squeeze from both high employment and CO_2 concentration I

In a steady state $\delta = g \Rightarrow \pi$ from investment demand. Then $\pi \Rightarrow u$ from *demand side* macro balance. In medium run we have $\pi = F(\lambda, G) = F(\kappa u/\xi, G)$ with negative partials from profit squeeze. Hence G and κ must trade off in steady state to hold π constant.

[Contrast, say, Solow model where $\delta = g = sf(\kappa, G)$ so $\delta \Rightarrow \kappa$ from *supply side*. Also $\partial f/\partial \mathrm{G} < 0$.]

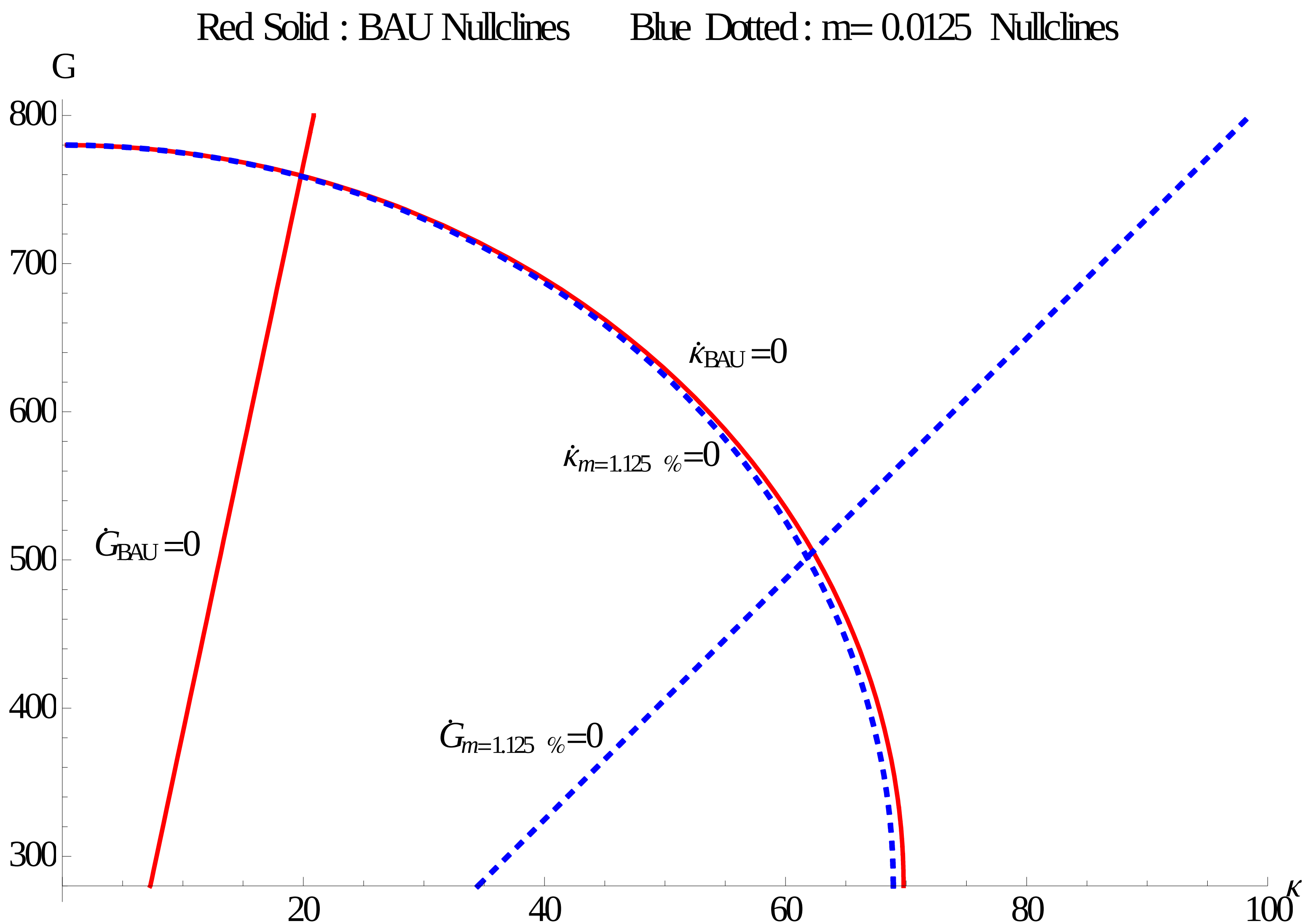
Steady state with profit squeeze from both high employment and CO_2 concentration II

Slope of the nullcline for G is sensitive to m so mitigation can support a non-dismal steady state.

But with no mitigation, $\kappa < 20$ and $G = 759$ in "business as usual"(BAU) dismal steady state (Initial values are $\kappa = 28.57$ and $G = 400.$)

Mitigated steady state $G = 486$ might correspond to $2.5°\mathrm{C}$ of global warming over the pre-industrial baseline – more than the currently accepted "red line"; BAU steady state with $G = 759$ would mean 5 or $6°\mathrm{C}$ of warming.

Nullclines for per capita capital stock (κ) and CO_2 concentration (G) when the profit share decreases with both G and κ



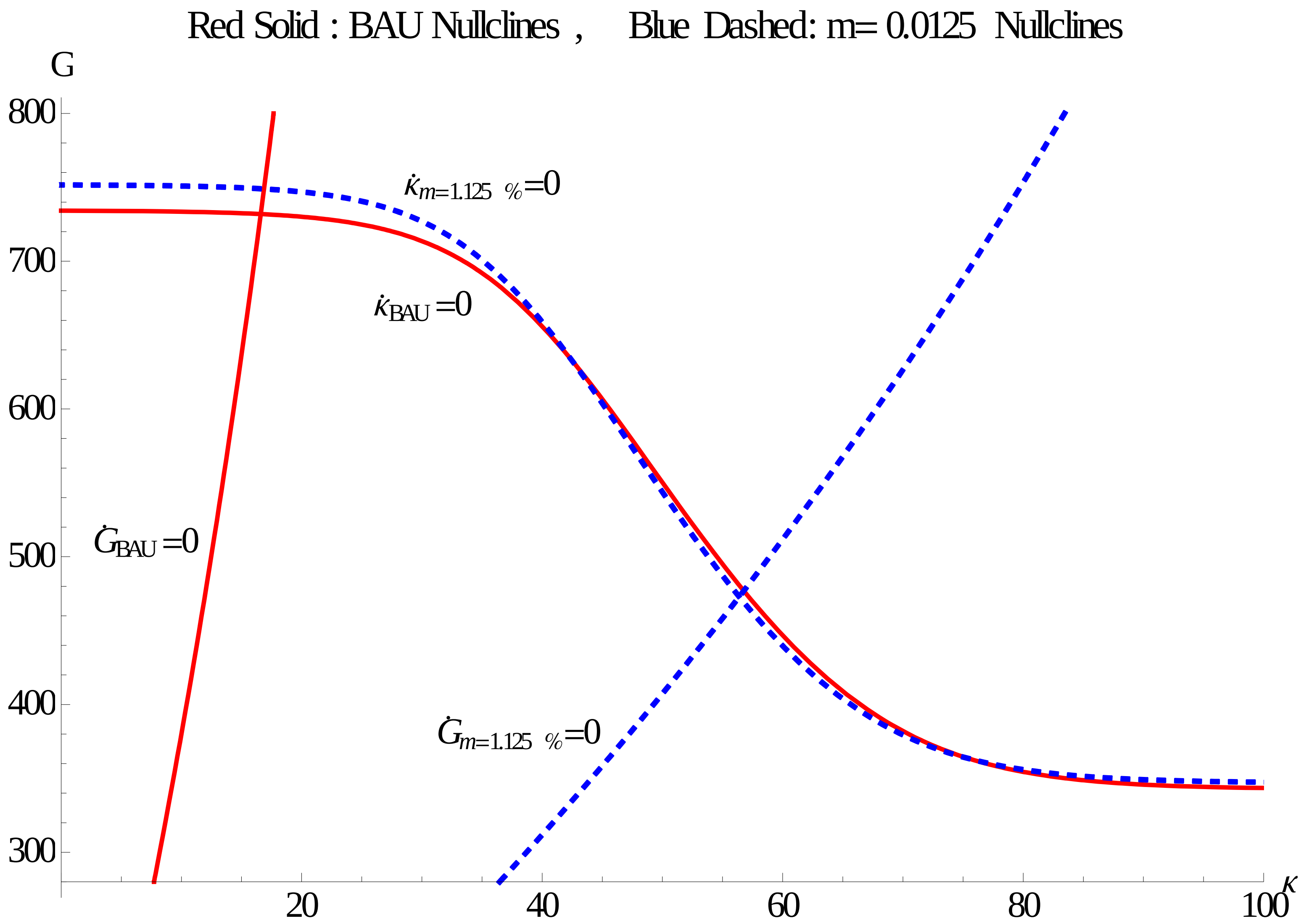
Steady state with capital destruction

In the second medium run variant, there is no direct adverse effect of G on π, but higher CO_2 concentration raises the depreciation rate δ – there is destruction of capital stock.

Now in steady state, higher G and δ must lead to higher π (investment is profit-led). But a higher π must be associated with a lower κ via lower λ.

Again we get a trade-off between G and κ. Mitigation can again support a high level steady state. No mitigation leads to low level stagnation.

Nullclines for capital stock per capita (κ) and CO_2 concentration (G) when higher G increases capital depreciation.



Levels of Key Variables in Steady States

Profit share decreases with both κ and G			
	Initial value	BAU	Mitigated
G	400	759.4	486.2
κ	28.6	19.8	63.0
X/N	8.6	5.6	18.3
λ	0.429	0.153	0.5
Higher G increases depreciation rate			
G	400	698.6	464.7
κ	28.6	20.3	57.3
X/N	8.6	6.6	17.2
λ	0.429	0.181	0.468

Steady state responses when the profit share decreases with both G and κ

Lots of numbers in next slides – note elasticities with respect to N, ξ, and m.

Higher steady state population strongly reduces κ and X/N under BAU; relatively weak impact on G. Magnitudes reverse in mitigated solution.

Higher labor productivity (which also raises energy productivity) increases κ, G, and X/N, more strongly in mitigated solution.

Higher m has generally beneficial effects.

Derivatives of κ, G, u and λ, wrt select magnitudes at steady state when the profit share decreases with both G and κ

Re[illegible]	BAU	MITIGATED
	sw	sw
d [illegible]	27.5363	62.0069
d [illegible]	−28.4175	−250.939
d [illegible]	−0.438389	−0.475731
d [illegible]	−0.023337	−0.323615
d [illegible]	−0.859272	−11.8942
	sπ	sπ
d [illegible]	10.0479	21.8808
d [illegible]	−10.3695	−88.5503
d [illegible]	−0.180331	−0.166749
d [illegible]	−0.0194971	−0.112268
d [illegible]	−0.717017	−4.12638
	N	N
d [illegible]	−1.87739	−2.11765
d [illegible]	3.98185	33.9201
d [illegible]	−0.00148978	−0.0193239
d [illegible]	−0.0153296	−0.0498982
d [illegible]	−0.538804	−0.616721
	ξ	ξ
d [illegible]	0.0282638	1.13426
d [illegible]	1.08369	9.20904
d [illegible]	−0.000405454	−0.00524628
d [illegible]	−0.00417233	−0.013581
d [illegible]	0.0081116	0.330331

Re[illegible]	BAU	MITIGATED
	e	e
d [illegible]	0.173074	6.94567
d [illegible]	6.63598	56.3917
d [illegible]	−0.00248281	−0.0321257
d [illegible]	−0.0255493	−0.0831638
d [illegible]	0.0496715	2.02278
	χ	χ
d [illegible]	−66.8586	−365.036
d [illegible]	141.804	5847.09
d [illegible]	0.95911	1.68839
d [illegible]	−0.00012202	−0.000685853
d [illegible]	−19.1882	−106.309
	m	m
d [illegible]	1199.28	6181.23
d [illegible]	−2584.55	−100014.
d [illegible]	−17.2041	−28.5899
d [illegible]	0.00218875	0.0116137
d [illegible]	356.553	1840.61
	δ	δ
d [illegible]	−124.275	−1307.77
d [illegible]	−947.702	−8049.28
d [illegible]	1.78277	6.0488
d [illegible]	−0.000226809	−0.00245712
d [illegible]	−35.6666	−380.861

Elasticities of κ, G, u and λ, wrt select magnitudes at steady state when the profit share decreases with both G and κ

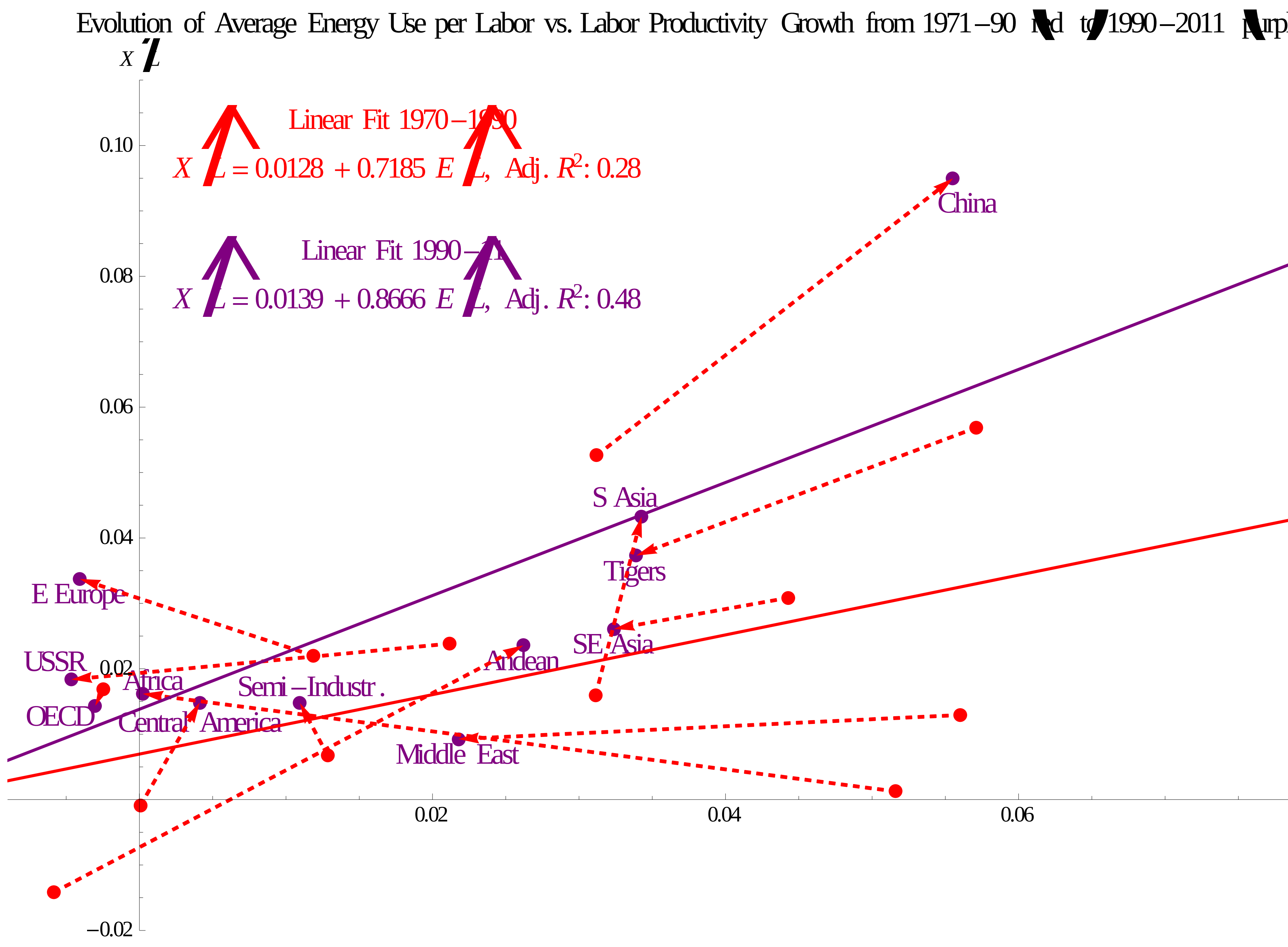
Elasticity	BAU	MITIGATED
	sw	sw
E [illegible]	0.296497	0.210116
E [illegible]	−0.00798269	−0.110093
E [illegible]	−0.328973	−0.34845
E [illegible]	−0.0324758	−0.138333
E [illegible]	−0.0325534	−0.138416
	$s\pi$	$s\pi$
E [illegible]	0.142003	0.0973169
E [illegible]	−0.00382319	−0.0509905
E [illegible]	−0.177615	−0.160306
E [illegible]	−0.0356115	−0.0629886
E [illegible]	−0.0356535	−0.0630267
	N	N
E [illegible]	−0.947583	−0.336373
E [illegible]	0.0524319	0.697588
E [illegible]	−0.0524048	−0.66347
E [illegible]	−0.999986	−0.999842
E [illegible]	−0.956852	−0.336423
	ξ	ξ
E [illegible]	0.0524138	0.661962
E [illegible]	0.0524285	0.695837
E [illegible]	−0.0524014	−0.661805
E [illegible]	−0.999986	−0.999843
E [illegible]	0.0529265	0.662061

Elasticity	BAU	MITIGATED
	e	e
E [illegible]	0.0524138	0.661962
E [illegible]	0.0524285	0.695837
E [illegible]	−0.0524014	−0.661805
E [illegible]	−0.999986	−0.999843
E [illegible]	0.0529265	0.662061
	χ	χ
E [illegible]	−0.947583	−1.62817
E [illegible]	0.0524319	3.37659
E [illegible]	0.947359	1.62779
E [illegible]	−0.000223508	−0.0003859
E [illegible]	−0.956852	−1.62842
	m	m
E [illegible]	0.	1.22731
E [illegible]	0.	−2.57106
E [illegible]	0.	−1.22701
E [illegible]	0.	0.000290889
E [illegible]	0.	1.25507
	δ	δ
E [illegible]	−0.326176	−1.0802
E [illegible]	−0.0648913	−0.860799
E [illegible]	0.326099	1.07994
E [illegible]	−0.0000769356	−0.000256021
E [illegible]	−0.329366	−1.08036

Dynamics III – Productivity growth

These steady state results presuppose constant levels of population (initial level = 7 billion, final = 10), energy intensity $e = E/L$ (initial = 4 kilowatts per employed worker, final = 6) and labor productivity $\xi = X/L$ (initial = \$20,000/worker, final = \$35,000)

See next slide for empirical linkages between growth rates of e and ξ – fairly strong relationships in both cross-section and time series.


Evolution of Average Energy Use per Labor vs. Labor Productivity Growth from 1971–90 red to 1990–2011 purpl
X/L
Linear Fit 1970–1990
X/L = 0.0128 + 0.7185 E/L, Adj. R²: 0.28
Linear Fit 1990–
X/L = 0.0139 + 0.8666 E/L, Adj. R²: 0.48
0.10
0.08
0.06
0.04
0.02
−0.02
0.02
0.04
0.06
China
S Asia
Tigers
SE Asia
Andean
E Europe
USSR
Africa
OECD
Central America
Semi–Industr.
Middle East

Period	Labor productivity elasticity w.r.t. energy labor ratio	Labor productivity elasticity w.r.t. energy productivity
1971-1990	0.4466	0.5534
1990-2004	0.7652	0.2348
2004-2011	0.8223	0.1777
1990-2011	0.8689	0.1311

Dynamics IV – Productivity growth

So an ostinato theme in Ecological Economics is that labor productivity is closely tied to energy intensity – (nearly) true historically.

Hence assume that producers choose a growth rate of energy intensity e that converges to steady state level, and labor productivity growth is determined as

$$\dot{\xi} = \xi T \hat{e}$$

with $T = 1.5$.

Energy productivity for use in $\dot{G}$ equation is set by the identity $\varepsilon = \xi / e$.

Transient paths to steady state – Business as usual (BAU) dynamics I

We set up simulations to track model dynamics toward a steady state. Growth trajectories are affected by assumed rates of increase of population, labor productivity, and energy intensity (logistic curves between initial and final levels).

First look at BAU growth when there is an adverse effect of CO_2 concentration on profitability (similar results when higher CO_2 increases depreciation rate).

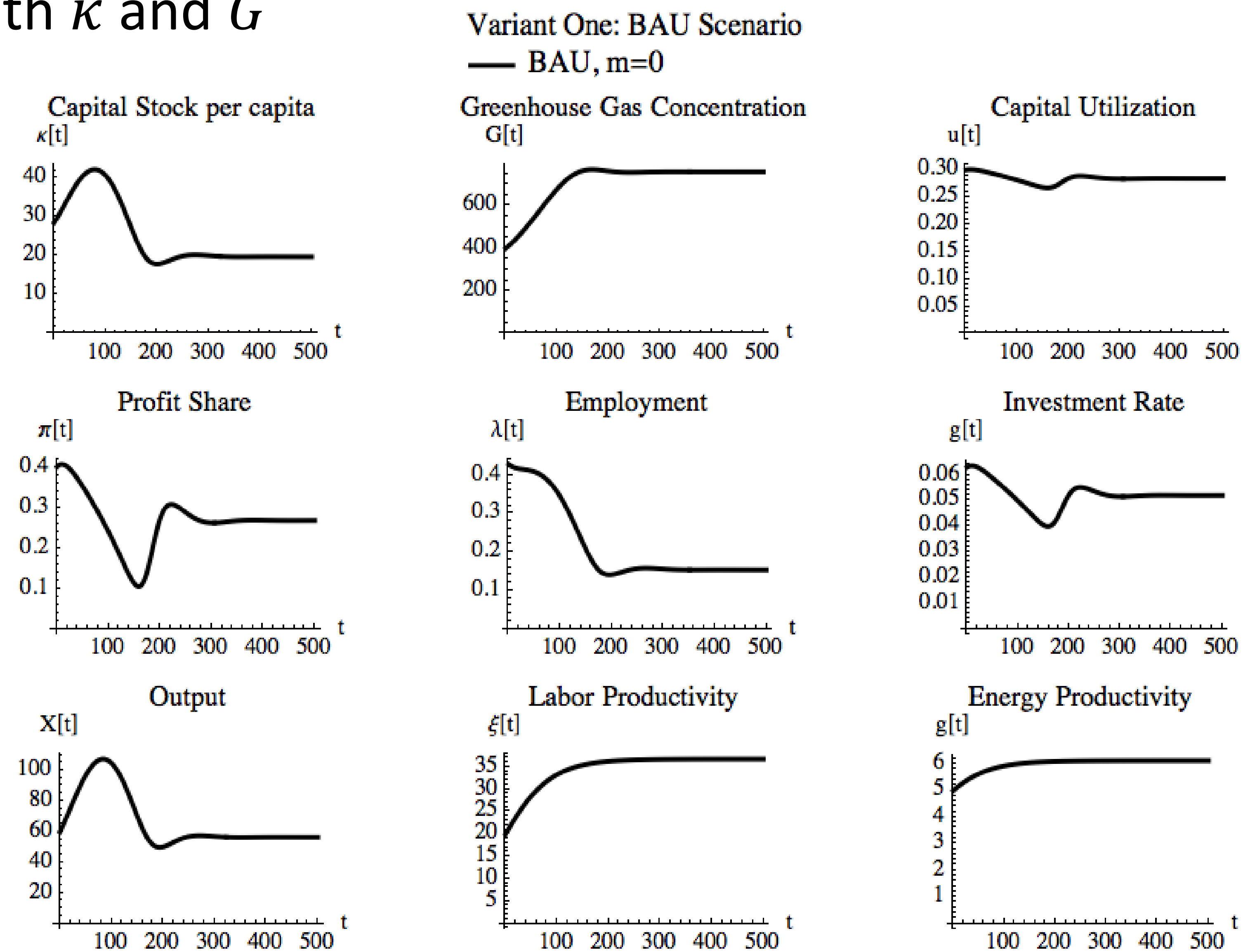
Transient paths to steady state – BAU dynamics II

Cyclical growth with crashes in capital per capita and output after around 8 decades.

CO_2 concentration *stabilizes* at well over 700 ppmv, so an atmospheric temperature increase of 5-6˚ Celsius. Output cannot recover.

Output stabilizes near its initial level of $60 trillion so output per capita falls by around 35% at a final population level of 10 billion.

BAU simulation when the profit share decreases with both κ and G



Transient paths to steady state – Climate mitigation dynamics I

Now look at growth with mitigation at initial cost of \$160 per metric ton of carbon, or \$44 per ton of CO_2 (mid-range of current estimates).

With mitigation outlay of 1.25% of world output (\$60 trillion initially) CO_2 concentration can be stabilized. This outlay is around one-half of current level of defense spending and roughly twice the level of worldwide energy consumption subsidies.

Transient paths to steady state – Climate mitigation dynamics II

The macro economy basically follows the growth path to a stationary state that would be observed in the absence of global warming.

BAU and 1.25% mitigation scenarios broadly correspond to the highest and lowest damage paths in the IPCC 2013

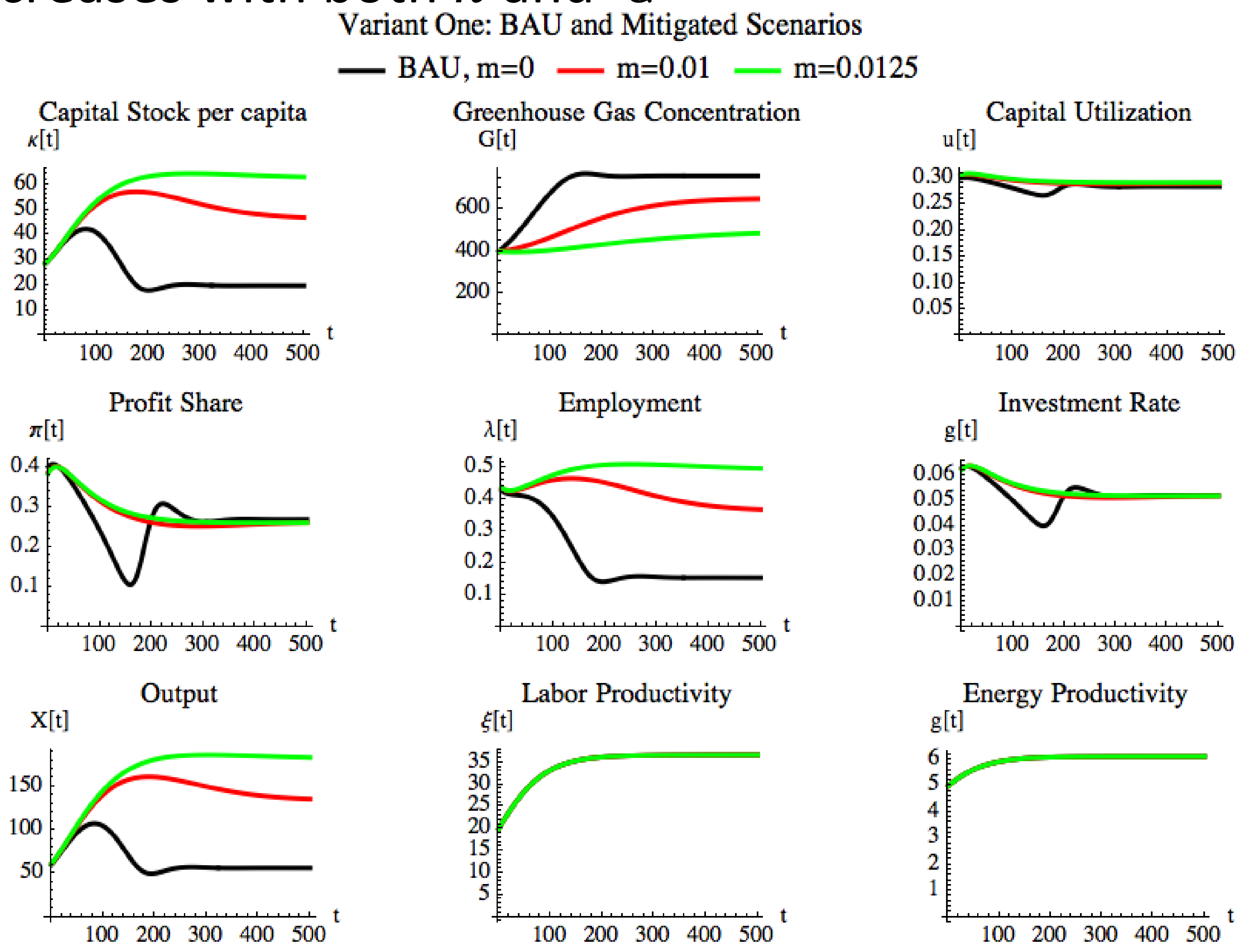
"Front-loading" mitigation leads to more favorable results ($G \approx 400$) – a "climate policy ramp" would be harmful.

Transient paths to steady state – Climate mitigation dynamics III

These results are largely driven by convergence dynamics of κ and G to steady state levels.

Same basic pattern appears under variant medium-run adjustments, e.g. higher CO_2 concentration reduces profitability *or* leads to capital destruction via faster depreciation *or* shifts down a neoclassical aggregate production function in a supply-driven full employment Solow growth model.

BAU and mitigation simulations when the profit share decreases with both κ and G



Transient paths to steady state – Impacts on labor I

Away from steady state, employment is determined as a "lump of labor," or $L = X/\xi$. Alternatively, since $\pi = F(\lambda, G) = F(\kappa u/\xi, G)$, $L = \lambda N$ is a function of π, G, and N.

Elasticity of λ w.r.t. ξ is -1 in both BAU and mitigated steady states. It is about -0.8 along transient paths ($\xi \uparrow \Rightarrow X \uparrow$).

BAU $steady$ $state$ λ is 65% below its initial value due to high G, stagnating X and increases over time in ξ and N. λ rises in mitigated solution.

Transient paths to steady state – Impacts on labor II

At steady state, $n = \widehat{N} = 0$, or gross investment = depreciation. Hence profit rate and saving can fall, or λ can rise slightly.

Real wage $\omega = (1 - \pi)\xi$.

The profit share stabilizes so that ω (not shown) can rise over time roughly in line with labor productivity.

So BAU gives a high wage (per unit labor) and low employment long run. Mitigated solution is high wage, high employment.

Transient paths to steady state – Impacts on labor III

There are potential positive feedback productivity linkages that we are considering

Kaldor: $\partial\dot{\xi}/\partial \mathrm{g} > 0$ so $\xi \uparrow \Rightarrow g \uparrow \Rightarrow \dot{\xi} \uparrow$

Induced innovation: $\partial\dot{\xi}/\partial \omega > 0$ so $\xi \uparrow \Rightarrow \omega \uparrow \Rightarrow \dot{\xi} \uparrow$

Kellogg-Sen: $\partial\dot{\xi}/\partial \lambda < 0$ so $\xi \uparrow \Rightarrow \lambda \downarrow \Rightarrow \dot{\xi} \uparrow$

Effects on employment to be explored.

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