WELFARE EFFECTS OF ADAPTATION TO CLIMATE CHANGE: RESULTS FROM A CALIBRATED MODEL

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February 2015

ABSTRACT

This paper examines a calibrated model of adaptation to climate change in which the availability of adaptation has the potential to be welfare-reducing in the non-cooperative equilibrium. Data on emissions and GDP for 180 countries are used to provide a guide to the relevant region of the parameter space. The predictions of the theoretical model are used to generate critical values for equilibrium adaptation levels at which adverse welfare effects arise, and the plausibility of these adaptation levels is then assessed. The results suggest that there are plausible scenarios under which the availability of adaptation could be welfare-reducing for all economies outside the EU, the US and China. The scenarios under which *all* countries would be better-off without adaptation are less plausible.

1. INTRODUCTION

As scientific evidence of anthropogenic climate change accumulates, and a comprehensive cooperative treaty to reduce global emissions remains elusive, the importance of adaptation as a strategic policy response is growing. This is a cause for concern among many small emitters. In particular, if the largest emitters turn increasingly towards adaptation as a substitute for abatement, then small economies – with no effective power to influence global emissions on their own – will be forced to engage in significant adaptation themselves despite their small contributions to the emissions that are causing their climates to change.

Farnham and Kennedy (2014) show that the availability of adaptation, and its substitution for abatement by large economies, could in fact make some small economies worse off overall. In particular, they argue that abatement is a public good but adaptation is a private good. Thus, substitution out of abatement and into adaptation by any one country imposes a negative externality on all other countries. Moreover, they show that the potentially deleterious impact of this substitution is asymmetric: small economies are most likely to be hurt by the availability of adaptation because they control only a small fraction of global emissions relative to the biggest emitters, and so have no scope to reduce global emissions unilaterally.

Our purpose in this paper is to investigate the Farnham-Kennedy (FK) hypothesis empirically using a calibrated version of their model based on data on GDP and emissions for 180 countries. Our results suggest that there are plausible scenarios with respect to adaptation costs under which all economies outside the top three (the EU, the US and China) would be better off if adaptation was not available to any country. In contrast, the top three economies would be unlikely to benefit from the unavailability of adaptation.

These results do not provide goods news for the many small countries that are increasingly concerned by the absence of a global treaty to reduce emissions. For these countries, the availability of adaptation could be more of a curse than a cure. They may nonetheless be forced to pursue significant adaptation as a best-response to the inaction of the largest emitters with respect to abatement. Thus, the countries that rely most heavily on adaptation in equilibrium are the same countries that would most likely benefit if adaptation was not available at all.

The paper is organized as follows. Section 2 presents a brief overview of the theoretical literature on adaptation to date, and places the FK model in the context of that literature. Section 3 provides an outline of the FK model and its key results. Section 4 describes the calibration methodology, and Section 5 presents the simulation results. Section 6 provides some concluding remarks.

2. ADAPTING TO CLIMATE CHANGE: THEORETICAL PERSPECTIVES

The theoretical work on adaptation to date can be loosely partitioned into two categories: central planning models; and strategic interaction models. A key concern of the former is the optimal mix of abatement and adaptation from a global perspective, and this in turn depends crucially on whether adaptation and abatement are substitutes or complements. Lecocq and Shalizi (2007) and Ingham *et. al.* (2013) argue that they are best viewed as substitutes. In contrast, Yohe and Strzepeck (2007) argue that they should be more sensibly treated as complements if the climate damage function is not as smooth and monotonic as is often assumed.

Kane and Shogren (2000) and Tulkens and van Steenberghe (2009) examine the impact of climate change *risk* on the optimal mix in the central planning solution. Ingham *et. al.* (2007) also examine a setting with uncertainty but with the possibility of learning. They argue that the availability of adaptation makes it more likely that a delayed abatement policy is optimal, because adaptation provides some insurance against an *ex post* mistake that leads to under-abatement.

Bréchet *et. al.* (2010) introduce economic growth into the planning problem, and argue that the optimal mix of abatement and adaptation for any given country depends on its stage of economic development. This in turn has important implications for how a global treaty might assign abatement requirements for developed versus developing countries.

The study of adaptation in settings with strategic interaction is for the most part more recent. Buob and Stephan (2011) consider a non-cooperative game among countries, and examine the equilibrium mix of abatement and adaptation. They show that equilibria with adaptation-only or abatement-only can arise when the two actions are perfect substitutes but equilibria with a mix of actions typically arise when they are complements. Ebert and Welsch (2011 and 2012) also study a non-cooperative game between countries, and show that the availability of adaptation as a substitute for abatement can mean that emissions become strategic complements. They also examine the welfare implications of differential adaptation costs among countries in the non-cooperative game.

The importance of strategic interaction between countries has also motivated work on the role of adaptation in shaping *cooperative* action on climate change. Barrett (2008) argues that the availability of adaptation can improve the prospects for cooperation via its impact on the non-cooperative payoffs, though only under scenarios where the realized gains from cooperation are relatively small. Buob and Stephan (2013) examine the implications of a cooperative agreement in which developed countries provide adaptation-funding assistance to developing countries. They argue that such assistance could actually reduce developing-country welfare because it shifts the burden of abatement away from developed countries.

The FK model focuses on strategic interaction between countries of different economic size. A key implication of this heterogeneity is that small economies have very little scope of control over global emissions, and this puts them at a strategic disadvantage in a game where abatement and adaptation are substitutes. The next section describes the FK model in more detail.

3. ADAPTATION AND THE SCOPE OF CONTROL OVER EMISSIONS

The following provides a sketch of the FK model. Our purpose is to provide only enough detail to inform and motivate the calibration and the simulation experiment. Readers are directed to the original article for more detail and discussion.

Let z_{ik} denote emissions from sector *k* in country *i*:

(1) $$z_{ik} = (1 - x_{ik})q_{ik}$$

where $x_{ik} \in [0,1]$ is the *abatement technology* used by sector *k*, and q_{ik} is the output from that sector. Abatement cost for sector *k* is

(2) $$c_x(q_{ik}, x_{ik}) = x_{ik}^2 q_{ik}$$

Thus, abatement cost is increasing and strictly convex in x_{ik} but linear in output.

Country *i* sets a regulatory target for domestic emissions $e_i = \sum_{k=1}^{n} z_{ik}$, where *n* is the number of sectors. The implementation problem for country *i* is to minimize aggregate abatement cost subject to meeting that emissions target:

(3) $$\min_{\{x\}} \sum_{k=1}^{n} x_{ik}^2 q_{ik} \quad \text{subject to} \quad \sum_{k=1}^{n} (1 - x_{ik}) q_{ik} = e_i$$

The interior solution is

(4) $$x_{ik} = 1 - \frac{e_i}{y_i} \quad \forall k$$

where $y_i = \sum_{k=1}^{n} q_{ik}$ is aggregate production in country *i*, which is taken to be its GDP. This least-cost solution can then be implemented via a domestic cap-and-trade system or a carbon tax.

Solution (4) tells us that all firms in country *i* use the same technology at the domestic optimum: $x_i = 1 - e_i / y_i$. Setting $x_{ik} = x_i$ in (1) and summing across *k* then yields a simple relationship between domestic emissions, the abatement technology and GDP:

(5) $$e_i = (1 - x_i) y_i$$

Aggregate abatement cost for country *i* is then constructed by setting $x_{ik} = x_i$ in (2) and summing across *k* to yield

(6) $$c_x(x_i, y_i) = \sum_{k=1}^{n} x_{ik}^2 q_{ik} = x_i^2 y_i$$

Aggregate global output is $Y = \sum_{i=1}^{N} y_i$ where *N* is the number of countries. The mean national output is μ, and $S = \sum_{i=1}^{N} y_i^2$ is the sum of squared national outputs. Global emissions are denoted $E = \sum_{i=1}^{N} e_i$. Damage from climate change is proportional to *E*. In particular, in the absence of adaptation, climate change destroys some fraction δE of the output in any given country, where δ is the *damage parameter*.

Adaptation is modeled as defensive action taken by country *i* to protect some fraction $a_i \in [0,1]$ of its economy from the damaging impact of climate change. The "undefended" residual fraction of the economy remains subject to damage. Thus, damage in country *i* is

(7) $$d_i = \delta E(1-a_i)y_i$$

The cost of adaptation for country *i* is strictly convex in its coverage, and proportional to the magnitude of economic activity that must be defended. In particular,

(8) $$c_a(a_i, y_i) = \theta a_i^2 y_i$$

where $\theta > 0$ is a parameter reflecting the cost of adaptation relative to the cost of abatement.

The policy problem for country *i* is to set a_i and x_i to minimize its total domestic cost (equal to the sum of domestic abatement cost, domestic adaptation cost, and domestic damage):

(9) $$\min_{a_i, x_i} \; x_i^2 y_i + \theta a_i^2 y_i + (1-a_i)\delta y_i[(1-x_i)y_i + E_{-i}]$$

where E_{-i} denotes aggregate emissions from all countries other than country *i*. The solution to this problem yields best response functions for the technology choice and adaptation in terms of E_{-i}, and these best response functions solve for an equilibrium that is stable and interior (in the sense that all countries have positive emissions) if $\delta < 2/Y$ and $\theta \geq \delta Y/2$. These parameter restrictions are henceforth assumed. Equilibrium emissions for country *i* are

(10) $$\hat{e}_i = y_i - \phi y_i^2$$

where

(11) $$\phi \equiv \frac{2\delta\theta - \delta^2 Y}{4\theta - \delta^2 S} > 0$$

and equilibrium adaptation for *every* country is

(12) $$\hat{a} = \frac{\delta(2Y - \delta S)}{4\theta - \delta^2 S}$$

Thus, all countries choose the same level of defensive action but the mix of abatement and adaptation differs across countries. In particular, small economies rely most heavily on adaptation because they have little control over global emissions; their best policy is to defend themselves against the damaging impact of those emissions via adaptation.

Welfare Properties of the Equilibrium

The key welfare properties of the equilibrium are stated as Propositions 3 and 4 in the FK paper, and they are restated here correspondingly (without the proofs) as welfare results 1 and 2.

WELFARE RESULT 1 (WR1)

(a) A marginal *increase* in θ is welfare-improving for country *i* if and only if

(13) $$y_i^2 < S - \frac{2Y - \delta S}{4\phi}$$

(b) Country *i* would be better off if adaptation was universally *unavailable* if and only if

(14) $$y_i^2 < S - \frac{2Y - \delta S}{2\phi + \delta}$$

Condition (13) is sufficient for condition (14) but the converse is not true.

WELFARE RESULT 2 (WR2)

(a) Total global cost is decreasing in θ if and only if

(15) $$Q < YS - \frac{(2Y - \delta S)Y}{4\phi}$$

where

(16) $$Q = \sum_{i=1}^{N} y_i^3$$

(b) Total global cost is lower when adaptation is universally *unavailabl*e if and only if

(17) $$Q < YS - \frac{(2Y - \delta S)Y}{2\phi + \delta}$$

Condition (15) is sufficient for condition (17) but the converse is not true.

These results – explained in more detailed in the original FK paper – reflect the fundamental difference between abatement and adaptation: abatement is a public good while adaptation is a private good. If the cost of adaptation rises then all countries substitute out of adaptation and into abatement. This move into abatement bestows a positive externality on all other countries. Thus, the potential exists for at least some countries to benefit overall when the cost of adaptation rises. The countries most likely to benefit are those with small economies. These countries receive a large external benefit when large economies raise their abatement because those large economies have such a large impact on global emissions. Conversely, small economies bestow only a small external benefit on large economies because the emissions from small economies are so small to begin with. This asymmetry explains the partitioning of countries according to income with respect to the welfare effect of a rise in θ, as described in WR1.

Because the impact of a change in θ differs across countries, a change from any initial value could be welfare-improving for some countries but not for others. Total global cost could therefore move in one direction or the other. WR2 pins down conditions on the distribution of GDP that determine the direction of change in total global cost associated with a marginal increase in θ, and with adaptation becoming unavailable entirely. These conditions hinge on the skewness of the GDP. If the distribution has a large positive skewness – as the true GDP distribution does – then global GDP is dominated by a relatively small number of large economies. The impact of adaptation on global cost is therefore governed mostly by its impact on the costs of the largest economies, and we know from WR1 that the largest economies tend to benefit more from the availability of adaptation than do small economies. Thus, global cost is increasing in θ unless skewness is very small.

4. THE CALIBRATION METHOD

Expression (10) predicts a relationship between GDP and equilibrium emissions that hinges on ϕ, as defined in (11). Thus, to calibrate the model, we estimate ϕ from data on carbon dioxide emissions and GDP for 153 economies (where the EU is aggregated into a single economy). The source of all data is the World Bank's *World Development Indicators 2013*. GDP is calculated in current US dollars. All data is for 2010, the most recent year for which comprehensive cross-country data is currently available.

It is important to stress that we do not claim to provide an estimate of the true relationship between emissions and GDP here. Many factors beyond GDP determine cross-country emissions in practice – industrial composition and *per capita* GDP being obvious additional candidate determinants – and we make no attempt to control for those other factors here. Our purpose is limited to generating a ball-park value for ϕ by forcing the data to reflect the simple structure of the theoretical model, given the actual distribution of global output. Accordingly, our econometric method for the estimation is deliberately rudimentary so as not to misrepresent our intent.

The three largest economies in 2010 (in descending order) were the EU, the US and China. Together these three economies accounted for 60% of global GDP. The three largest emitters (in descending order) were China, the US and the EU, and together they accounted for 57% of global emissions. Not surprisingly, the relative positions of these three economies – in terms of GDP and emissions – have a dominating influence on the estimate for ϕ.

The estimated equation is

(18) $$e_i = \beta_1 y_i - \beta_2 y_i^2$$

where β_1 is estimated freely because the units in which emissions are measured in the model are arbitrary. The OLS regression results are reported in Table 1. Normalizing units for emissions to fit equation (10) produces a point estimate for ϕ equal to

(19) $$\hat{\phi} = \frac{\hat{\beta}_2}{\hat{\beta}_1} = 3.6015E-05$$

The 95% confidence interval for ϕ is $3.12E-05$ to $4.09E-05$.[1] The other parameters needed for the calibration can be calculated directly from the 2010 GDP data. These are $\hat{Y} = 69462$, $\hat{S} = 5.6553E08$ and $\hat{Q} = 7.2761E12$.

Note that the estimate for ϕ does not allow δ and θ to be identified separately. This would require data on adaptation actions, which is not currently available. However, using equation (11) we can express θ in terms of ϕ and δ:

(20) $$\theta = \frac{(Y - \phi S)\delta^2}{2(\delta - 2\phi)}$$

[1] Constructed using the delta method routine in *Stata*.

Thus, for every possible value of δ there is a unique corresponding value of θ implied by the estimate for ϕ. This in turn allows equilibrium adaptation to be expressed in terms of δ and $\hat{\phi}$, or equivalently, for δ to be expressed in terms of ϕ and equilibrium adaptation:

(21) $$\delta = \frac{2\phi}{1-a}$$

One can therefore cast the critical conditions from WR1 and WR2 in terms of the level of adaptation that would need to arise *in equilibrium* for those conditions to hold, given the estimate for ϕ. One can then ask whether that level of adaptation seems *plausible*. For example, suppose a country is made better off by the availability of adaptation only if equilibrium adaptation protects more than 99% of its economy from damage. That level of adaptation seems implausibly high, so it seems reasonable to believe that this country is in fact made worse off by the availability of adaptation. Using this approach allows some reasonable judgments to be made despite the absence of data on actual adaptation actions.

5. SIMULATION RESULTS

Recall that WR1 and WR2 respectively correspond to welfare results for individual countries, and for the global economy as a whole. We begin with the individual-country results, and then turn to the global results.

5.1 Individual Country Results

Using (20) and (21), the threshold income levels from parts (a) and (b) of WR1 can be written as

(22) $$\tilde{y} = \left(\frac{(3-2a)\phi S - Y(1-a)}{2\phi(1-a)} \right)^{\frac{1}{2}}$$

and

(23) $$\bar{y} = \left(\frac{(3-a)\phi S - Y(1-a)}{\phi(2-a)} \right)^{\frac{1}{2}}$$

respectively, where *a* is *equilibrium* adaptation.

Figure 1 plots $\tilde{y}$ and $\bar{y}$ against *a*, evaluated at $\phi = \hat{\phi}$. The vertical axis uses a log scale for income, and the axis is abbreviated at $\log(\mu)$ so as to focus on the most interesting region of the GDP space. Any point to the left of the $\tilde{y}$ curve represents an $\{a, y\}$ pair such that condition (13) holds: an economy with GDP equal to that value of y would benefit from a marginal reduction in θ if the actual equilibrium adaptation level is a. Similarly, condition (14) holds at any point to the left of the $\bar{y}$ curve. The upper horizontal line labeled y_1 identifies the GDP of the EU (the largest economy), while the lower horizontal line labeled y_4 identifies the GDP of Japan (the fourth largest economy, behind the EU, US and China).

The figure conveys three key messages. First, if $a \leq 0.29$ (meaning that less than 29% of economic activity is defended against climate change in equilibrium) then every country would benefit from a *marginal reduction* in θ. Conversely, if $a > 0.55$ then no country would benefit. Second, if $a \leq 0.17$ then every country benefits from the availability of adaptation but if $a > 0.44$ then no country benefits.

Third, there is little difference between the value of *a* at which every economy benefits from the availability of adaptation, and the value at which no economy *outside the top three* benefits; the GDP distribution is effectively bifurcated into two groups. This is especially true with respect to availability: every country benefits if $a \leq 0.17$ but no country outside the top three benefits if $a > 0.20$. This reflects the extreme skewness of the GDP distribution, and the associated skewness of the distribution of emissions.

An equilibrium outcome in which around 20% of economic activity is effectively defended against climate change certainly seems plausible, but one cannot make a stronger statement than that given the absence of additional data. It is nonetheless interesting to ask what the magnitude of the benefit from universal unavailability of adaptation might be if *a* is indeed equal to that value. By setting $a = 0.20$ and $\phi = \hat{\phi}$ one can calculate the implied values of δ and θ, and then calculate for each country the cost difference between the equilibrium (where $a = 0.20$) and the outcome where adaptation is unavailable (by taking the limit as $\theta \to \infty$). For the median country within the group of winners (those outside the top three economies), the benefit is 1.34% of GDP. The average gain within the group is 1.32% and the total gain for the group, expressed as a fraction of total GDP for the group, is 1%. However, these gains come at great cost to the global economy as a whole: the *net* benefit of making adaptation unavailable to the global economy when $a = 0.20$ is *negative* 6.06% of global GDP.

Sensitivity Testing

These quantitative results are of course sensitive to the estimated parameter ϕ. Table 2 reports key threshold values for *a* evaluated at $\hat{\phi}$, and at the lower and upper bounds of the 95% confidence interval around $\hat{\phi}$, focusing on the universal unavailability scenario. (The sensitivities are comparable for the marginal cost increase scenario). The table is read as follows. The first data column reports $\bar{a}_L$, the value of equilibrium adaptation below which no country benefits from making adaptation unavailable. The second data column reports $\bar{a}_4$, the value above which all economies outside the top three benefit. The third data column reports $\bar{a}_1$, the value above which all countries benefit. The fourth data column reports the average gain within the group of winners (those outside the top three) if $a = \bar{a}_4$. The fifth data column reports the global net benefit if $a = \bar{a}_4$.

The reported values are clearly sensitive to the estimate for ϕ but on balance they indicate that there are plausible values of *a* at which all but the top three economies would benefit from making adaptation unavailable. However, the cost to the global economy as a whole is large, especially at the upper bound value of ϕ.

5.2 Aggregate Results

We now turn to the subject of Result 2: under what conditions would the global economy as a whole derive a positive net benefit if adaptation became more costly? We confine consideration to part (b) of that result, pertaining to making adaptation universally unavailable. The calibrated results are summarized in Table 3. The first data column reports the threshold value of equilibrium adaptation (denoted $\bar{a}$ in the table) above which universal unavailability has a positive net benefit (such that the gains to the small-country winners more than offset the losses to the large-country losers). At any $a < \bar{a}$, unavailability of adaptation would yield a negative net benefit. The second data column reports the GDP-rank and identity of the marginal beneficiary from unavailability if $a = \bar{a}$. The final data column reports the percentage reduction in global emissions that unavailability would induce if $a = \bar{a}$.

The results provide two key messages. First, the equilibrium adaptation level would have to be fairly high before unavailability would produce a net benefit to the global community as a whole, though the upper-bound value of ϕ produces a plausible scenario (where $\bar{a} = 0.17$). At the threshold where the net benefit is just equal to zero (where $a = \bar{a}$), the split between winners and losers is stark: in all cases the US and the EU would lose and all other countries would benefit (where China is the marginal beneficiary).

Second, making adaptation unavailable when $a = \bar{a}$ would cause a fairly substantial reduction in global emissions (at all three values of ϕ). This of course reflects the forced substitution into abatement that making adaptation unavailable would precipitate. One can also usefully frame this relationship in terms of its converse. In particular, if the unavailability of adaptation induced a reduction in global emissions of more than 17.9% (in the $\phi = \hat{\phi}$ case) then that unavailability would yield a positive net benefit.

6. CONCLUSION

The results of this calibration suggest that there are plausible scenarios under which the availability of adaptation could be welfare-reducing for all economies outside the top three. On balance, the scenarios under which *all* countries would be better-off without adaptation are less plausible.

It is important to stress the limitations of this analysis. In particular, the estimation of the GDP-emissions relationship should not be interpreted as a serious attempt to quantify that relationship as it might exist in practice. Its purpose is only to provide a guide to the region of the parameter space to which the theoretical model might reasonably apply. Nonetheless, the results of the calibration indicate that the potential for adverse welfare effects is not simply a theoretical curiosity. There appears to be a realistic possibility that the predictions of the model are of practical relevance.

That conclusion of course raises an important question: what can be done to address this potential adverse effect of adaptation? Putting limits on adaptation is clearly not a realistic policy option, and certainly not one that any single country would rationally adopt unilaterally. Integrating adaptation policy into a global treaty on climate change could in principle help to alleviate the problem but this too would be difficult in practice. Emissions are relatively easy to monitor under a treaty but adaptation is a multi-faceted activity and one that would be difficult to quantify and monitor. Moreover, adding additional components to the scope of a global treaty is unlikely to make such a treaty any easier to negotiate, and the task already appears to be a very challenging one.

Perhaps the clearest message from this analysis is that small economies must be realistic about what their climate-change priorities should be in a world without cooperative action to reduce emissions. An emphasis by large economies on adaptation over abatement might be to the detriment of smaller economies but – paradoxically – the best response for those small economies is to focus heavily on adaptation themselves. In particular, in allocating scarce resources to an effective strategy against climate change, small countries are likely to be much better served by investing in adaptation measures than by adopting cleaner technologies.

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Variable	Coefficient	S.E.	*t* value	95% Confidence Interval	
GDP	0.7396889	0.0464609	15.92	0.6478916	0.8314863
GDP^2	– 0.0000266	– 3.43 E–06	– 7.75	– 0.0000334	– 0.0000198
Goodness of Fit		$F(2, 151)$	R^2	$adjR^2$	Root M.S.E.
		467.81	0.8610	0.8592	316.02

TABLE 1: OLS REGRESSION RESULTS

Evaluated at	$\bar{a}_L$	$\bar{a}_4$	$\bar{a}_1$	Average benefit at $a = \bar{a}_4$ (% of GDP)	Global net benefit at $a = \bar{a}_4$ (% of GDP)
lower bound on ϕ	0.32	0.34	0.53	2.32	– 10.7
$\hat{\phi}$	0.17	0.20	0.44	1.32	– 6.06
upper bound on ϕ	0.002	0.03	0.34	0.23	– 1.04

TABLE 2: CALIBRATION OF RESULT 1B

Evaluated at	$\bar{a}$	Marginal Beneficiary (GDP rank)	Impact on Global Emissions (% reduction)
lower bound on ϕ	0.42	China (3)	24.5
$\hat{\phi}$	0.30	China (3)	17.9
upper bound on ϕ	0.17	China (3)	10.3

TABLE 3: CALIBRATION OF RESULT 2B

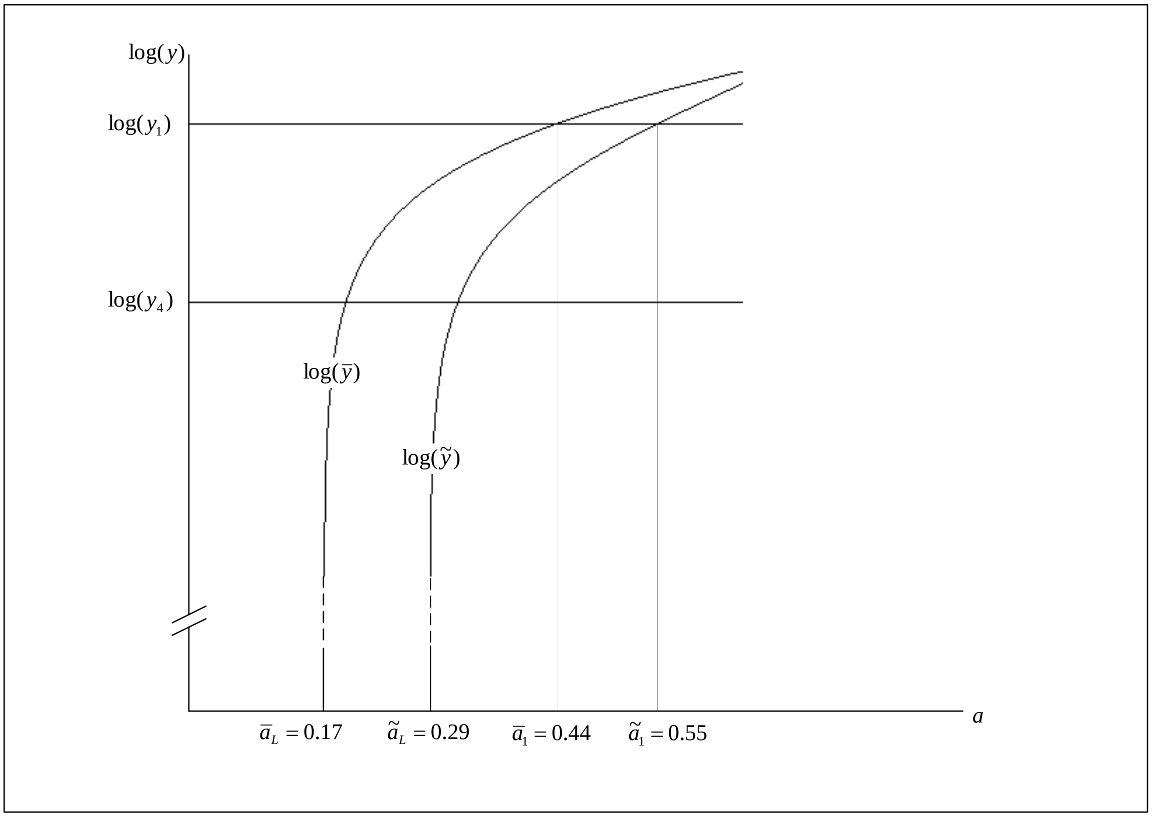

FIGURE 1: CALIBRATED INDIVIDUAL-COUNTRY RESULTS