Staff Paper Series

**Recalibrating the Reported Rates of
Return to Food and Agricultural R&D**

by

Xudong Rao, Terry M. Hurley and Philip G. Pardey

**Department of
APPLIED
ECONOMICS**

**INSTEPP
INTERNATIONAL
SCIENCE & TECHNOLOGY PRACTICE & POLICY**

HarvestChoice
BETTER CHOICES, BETTER LIVES

College of Food, Agricultural
and Natural Resource Sciences

UNIVERSITY OF MINNESOTA

Recalibrating the Reported Rates of
Return to Food and Agricultural R&D

by

Xudong Rao, Terry M. Hurley and Philip G. Pardey

ABSTRACT

Prices of basic food staples and feed crops have soared in recent years, renewing concerns about the ability of global food supplies to meet the projected growth in aggregate demand. Notwithstanding these concerns, and apparently at odds with a vast body of economic evidence reporting exceptionally high rates of return to investments in agricultural R&D, growth in public R&D spending for food and agriculture has slowed worldwide, especially in rich countries. Left unchecked, the consequent slowdown in agricultural productivity will push many more people into hunger and undercut economic growth, especially in the many economies worldwide still heavily reliant on agriculture. The observed R&D spending behavior is consistent with a determination that the rate of return evidence is implausible. We examine this notion, recalibrate a new, comprehensive compilation of the evidence, and find in favor of a much reduced rate of return to research. Nonetheless, the scaling back of public agricultural R&D spending is not supported from this new economic view of the evidence.

Recalibrating the Reported Rates of Return to Food and Agricultural R&D

More than half a century has passed since Zvi Griliches published the first formal economic

estimate of the returns to food and agricultural R&D in the *Journal of Political Economy*.[1] Since

then many economists have published a large number of similar estimates. Alston et al. (2000)

reported on 292 such studies with 1,886 evaluations of the payoffs to investments in agricultural

R&D either in the form of internal rates of return or benefit-cost ratios.[2] Averaging across all

studies, the internal rate of return was 81 percent per year, indicative of a widespread and

persistent underinvestment.[3] But rather than ramping up spending to more economically

justifiable amounts, growth in agricultural R&D spending worldwide has slowed for many

countries for each of the past five decades, particularly for the rich countries who collectively

accounted for 48 percent of the world's public expenditures in 2009 (Pardey, Alston and Chan-

Kang 2012).

One plausible explanation for this investment behavior is that economists got it wrong—

systematically overstating the estimated returns to R&D. Alternatively, but with equal effect,

those making R&D investment decisions may have simply dismissed the reported rates of return

to research as unbelievably high. There is certainly precedent for that perspective. McMillen's

1929 account of then U.S. Secretary of Agriculture "Tama Jim" Wilson's attempt to compile a

report on what, if any, profit could be shown to the country from the Department of Agriculture's

expenditures on research reads:

Numerous interests and industries were asked to estimate conservatively the value of

---

[1] Heckman (2006) wrote that "[Griliches] early empirical work on the social rate of return to research activity [Griliches 1958], and on the role of economic incentives in determining the distribution of benefits from new technologies [Griliches 1957], laid the foundations for scientific study of these topics."

[2] See also the summaries of this evidence by Evenson (2002) and Fuglie and Heisey (2007).

[3] Ruttan (1980 and 1982) presents arguments regarding the underinvestment hypothesis.

such of the department's findings as affected their operations. Finally the expenditures were totaled in one column, the estimates of the returns in another, and the sheets placed before the venerable secretary.

"This will never do!" he protested. "No one will swallow these figures!" The report revealed that for every single dollar that had been spent for scientific research in the Department of Agriculture, the nation was reaping an annual increase of nearly a thousand dollars in new wealth.

"Cut it down to $500," insisted Wilson. "That's as much as we can expect the public, or Congress, to believe."

<div align="right">(McMillen 1929, p. 141)</div>

The evident failure of the economic evidence to sway R&D investment decisions, especially in more recent decades, has profound consequences. Alston, Babcock and Pardey (2010) concluded that the presently available evidence points to a widespread (but not universal) slowdown in agricultural productivity growth, consistent with a prior and persistent ratcheting down in the rate of growth in agricultural R&D spending. If R&D-induced shifts in global food supplies fall short of corresponding shifts in aggregate demand, affordable access to food will be further curtailed, with inevitable negative consequences for the dismal tally of chronically hungry worldwide (Ivanic and Martin 2008).[4]

In this paper we address the question, is the reported rate of return evidence credible, and if not what can or should be done to recalibrate that evidence? To do so we develop and deploy a comprehensive compilation of rate-of-return (and associated benefit-cost) estimates published since 1958. We argue that the weight of evidence supports the conclusion that the vast majority of rate of return estimates are implausibly high and where data permit recalibrate these estimates into the more plausible, and conceptually more coherent, modified internal rates of return. While our analysis serves to downsize the overall average of the returns to food and agricultural R&D, the recalibrated evidence is still suggestive of significant underinvestment.

---

[4] FAO (2012) estimated there were 850 million chronically undernourished people in the world in 2006–08.

1. The Evidence at Face Value

The evidence we assembled includes 2,186 evaluations published in 359 separate studies between 1958 and 2011.[5] The investments covered in the dataset include those sponsored by governments, non-governmental organizations, and private companies.[6] These investments covered a wide range of commodities from many regions of the world. The sources for these evaluations include studies published in books, journals, and a good deal of grey literature (e.g., evaluation reports and studies published by various international and national agencies). The internal rate of return (*IRR*) was the predominant measure of returns to R&D reported by 95 percent of the studies. Alternatively, 26 percent of the studies reported a benefit-cost ratio (*BCR*), with 21 percent reporting both the *IRR* and *BCR*.

Figure 1 shows the kernel density estimate for the reported *IRR*s in addition to other descriptive statistics. The average *IRR* is 74.3 percent per year. The distribution is right skewed with a median of 43 percent per year. The minimum is a dismal -47.5 percent per year, while the maximum is an incredible 5,645 percent per year. Seventy-five percent of the reported *IRR*s exceed 24 percent per year.

[Figure 1: *Distribution of reported internal rates of return estimates*]

To gain some perspective on the implications of such high rates of returns, we evaluated just how much the $4.1 billion (2005 prices) invested in 2000 in agricultural R&D by the United States Department of Agriculture (USDA) and state agricultural experiment stations (SAES) (Alston et al. 2010) would be worth in 2050 assuming benefits accrued over 50 years, which is

---

[5] After correcting some errors (and dropping several studies that reported only producer or consumer surplus estimates) in the compilation developed for Alston et al. (2000), we added 77 new studies published during the period 1999-2011 which reported 510 additional IRRs or BCRs.

[6] Only 8 observations pertain to private research, two of which involve public-private collaborations in R&D.

not atypical for these types of investment (Alston et al. 2000).[7] At the average rate of return estimated in the literature, this investment would yield $4.7 sextillion in benefits by 2050.[8] At the median rate of return, which is a more robust measure of central tendency given some of the extreme *IRR* estimates in the literature, it would still be worth $240 quadrillion. Even the first quartile estimate would be worth $192 trillion. Comparing these results with U.S. and global gross domestic product (GDP) makes it hard not to question their plausibility. The U.S. GDP in 2000 was about $11 trillion (2005 U.S. dollars), while the world GDP was $38 trillion (Foure, Benassy-Quere and Fontagne 2010). By 2050, the forecasted GDP for the United States and the world are $28 and $148 trillion respectively (2005 U.S. dollars) (Foure, Benassy-Quere and Fontagne 2010). Therefore, the median *IRR* estimate in the literature suggests the benefits attributable just to public agricultural R&D investments by the United States in 2000 would be more than 1,600 times the projected world GDP in 2050!

Figure 2 shows the kernel density for the reported *BCR*s in addition to other descriptive statistics. The mean *BCR* was 23.3, which implies a more plausible return of $95.5 billion on a $4.1 billion investment in R&D. The median *BCR* of 11.0 implies a return of $45.1 billion, while the first quartile estimate of 3.2 implies a return of $13.1 billion. Compared with the returns implied by the *IRR* estimates, the *BCR* estimates are much more plausible, yet only one out of four studies that evaluated the returns to agricultural R&D reported the *BCR*.

[Figure 2: *Distribution of reported benefit-cost ratio estimates*]

---

[7] All estimates reported in this paper are in real 2005 U.S. dollars.

[8] The descriptive statistics reported in Figure 1 are for a mix of real and nominal rate of return estimates. The vast majority of the estimates were real (74.5 percent) with an average and median of 69.9 percent per year and 42 percent per year respectively. About one in five estimates (17.8 percent) were nominal with an average and median of 67.6 percent per year and 50 percent per year respectively. The balance, with an average and median of 132.6 percent per year and 35 percent per year, came from studies that did not specify whether the estimates were real or nominal.

2. Modified Internal Rate of Return

The *IRR* is defined as the discount rate that equates the net present value of an investment's costs to the net present value of its benefits. While the *IRR* has served as the predominant quantitative measure of returns in the agricultural R&D evaluation literature, it has been viewed critically by economists for more than half a century. Lorie and Savage (1955) pointed out the now well-known problem that the *IRR* need not be unique when costs accrue over time, which can confound its interpretation. Solomon (1956) argued that the problem with the *IRR*, exemplified by potential non-uniqueness, is that it is not actually a measure of an investment's worth. Hirshleifer (1958) delved deeper into the theoretical appropriateness of using the *IRR* for choosing investments concluding that it can be justified in a simple two- period model under some circumstances, but this justification does not extend to more than two periods. Hirshleifer noted, as did Baldwin (1959), that with more than two periods the *IRR* implicitly assumes that intermediate cash flows can be reinvested (or borrowed) at the same rate of return as the initial investment, which both argued was generally not correct or reasonable.

Griliches also expressed concerns about the *IRR*'s implicit reinvestment assumption when evaluating the returns to hybrid corn research in his seminal 1958 *Journal of Political Economy* article:

> My objection to this particular procedure is that it values a dollar spent in 1910 at $2,300 in 1933. This does not seem very sensible to me. I prefer to value the 1910 dollar at a reasonable rate of return on some alternative social investment.
> (Griliches 1958, p. 425).

Given such an objection, one might speculate why Griliches chose to report bounds for the *IRR* in addition to the *BCR* in his analysis. Such speculation is unnecessary however because Griliches clearly implicates Martin J. Bailey for suggesting the *IRR* calculation (Griliches 1958, p. 425, footnote 16) and ultimately determined "…the two estimates are not very far apart"

(Griliches 1958, p. 425). Regardless, the objections of Griliches and others to the *IRR* were

overlooked by agricultural R&D evaluation studies for more than half a century.

Criticisms of the *IRR* have not been devoid of suggestions for improvement, which has

resulted in the alternative modified internal rate of return (*MIRR*). Biondi (2006) noted that the

MIRR was actually first invented by Duvillard (1787) and then rediscovered amid the criticisms

of the *IRR* launched by Solomon (1956) and Baldwin (1959). Lin (1976) appears to be the first

to use the term "Modified Internal Rate of Return," though Athanasopoulos (1978) also refers to

the *MIRR* as the "Effective Rate of Return" arguing that it is not independent of the cost of

capital and therefore not internal.

The *MIRR* is defined as $\sqrt[T]{\frac{FVB}{PVC}} - 1$ where $T > 0$ is the term of the investment, $FVB \geq 0$ is the

future value of the investment benefits, and $PVC \geq 0$ is the present value of the investment costs.

The interpretation of the *MIRR* is more transparent when formulated implicitly as $PVC = \frac{FVB}{(1+MIRR)^T}$, which says it is the discount rate that equates the present value of costs and benefits.

While this interpretation appears identical to the *IRR*, there is a key difference. The discount (or

reinvestment) rate used to compute *FVB* and the discount (or cost of capital) rate used to

compute *PVC* need not be equal to each other or the *MIRR*. Indeed, the reinvestment and cost of

capital rates could vary over time in the computation of the *MIRR*, which Hirshleifer (1958)

argued would often be appropriate when evaluating investment options. By relaxing the *IRR*'s

implicit assumption that an investment's rate of return is equal to the reinvestment and cost of

capital rates, the *MIRR* addresses an important criticism of the *IRR*. It also addresses another

important concern about the *IRR* because the *MIRR* is unique.

More than half a century after Griliches' contribution, Alston et al. (2011) became the first to

address criticisms with using the *IRR* by applying the *MIRR* in the context of evaluating the

returns to agricultural R&D. Their research focused on USDA and SAES agricultural R&D investments from 1949 to 2002. They found that the average *IRR* across states was 22.7 percent per year with a range of 15.3 to 29.1 percent per year. Assuming a 3 percent per year reinvestment and cost of capital rate, the average *MIRR* was a more modest 9.9 percent per year with a range of 7.7 to 11.7 percent per year. These results raise an interesting and pertinent policy question. How attractive would previous estimates of returns to agricultural R&D be if they were based on the *MIRR* instead of the *IRR*? To answer this question, we first deconstruct previous rate of return estimates based on the *IRR* where feasible, and then reconstruct them using the *MIRR*.

3. Reconstructing Rates of Return Using the *MIRR*

The computation of the *MIRR* requires the term of the investment and the stream of benefits and costs in addition to the reinvestment and cost of capital discount rates. Athanasopoulos (1978) and Negrete (1978) noted an important relationship between the *MIRR* and *BCR*:

(1) $\quad MIRR = (1 + \delta)\sqrt[T]{BCR} - 1,$

where δ is the discount rate used to evaluate the *BCR* and *T* is the term of the investment. This relationship is convenient for recalibrating previous evaluations of R&D based on the *BCR* using the *MIRR*. However, such a recalibration still neglects the concern that the appropriate reinvestment rate need not equal the cost of capital rate, which is especially true for publicly funded agricultural investments where many benefits accrue privately (to both producers and consumers).

The simple relationship between the *MIRR*, *BCR* and δ in equation (1) can be generalized to account for differing discount rates:[9]

$$(2) \quad MIRR = \sqrt[T]{BCR \frac{\sum_{t=0}^{T} w_{c_t}(1+\delta)^{-t}}{\sum_{t=0}^{T} w_{b_t}(1+\delta)^{-t}} \frac{\sum_{t=0}^{T} w_{b_t}(1+\delta^r)^{T-t}}{\sum_{t=0}^{T} w_{c_t}(1+\delta^c)^{-t}}} - 1.$$

where w_{c_t} and w_{b_t} are the proportion of the total undiscounted costs and benefits accruing at time t, and δ^r and δ^c are the assumed reinvestment and cost of capital rates. Note that equation (2) reduces to (1) when $\delta = \delta^r = \delta^c$. More importantly, equation (2) says that the *MIRR* for previous studies can be calculated given the term of the investment, *BCR* and its associated discount rate, the distribution of costs and benefits, and the reinvestment and cost of capital rates. Unfortunately, while *T*, *BCR*, and δ are reported in many previous studies, seldom are the detailed distributions of costs and benefits. Therefore, calculation of the *MIRR* for previous studies requires some method for reconstructing the distributions of costs and benefits given commonly reported information.

There is a relationship between the *IRR* and *BCR* that can be exploited in an effort to reconstruct the distributions of costs and benefits:[10]

$$(3) \quad BCR = \frac{\sum_{t=0}^{T} w_{b_t}(1+\delta)^{-t}}{\sum_{t=0}^{T} w_{c_t}(1+\delta)^{-t}} \frac{\sum_{t=0}^{T} w_{c_t}(1+IRR)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+IRR)^{-t}}.$$

Equation (3) provides a direct relationship between the *BCR* and *IRR* that also depends on δ and the distributions of costs and benefits. This relationship is useful because it tells us which distributions of cost and benefits are consistent with the *T*, *BCR*, *IRR*, and δ reported in a study. Therefore, if we can identify distributions that reasonably satisfy equation (3), we can use these

---

[9] The details of this generalization are provided in the Appendix.

[10] The derivation of equation (3) is reported in the Appendix.

distributions with equation (2) to calculate the *MIRR* for any desired reinvestment and cost of capital discount rates.

We reconstructed the distributions of costs and benefits assuming each can be reasonably approximated with a two-parameter, unit trapezoidal distribution.[11] The unit trapezoidal distribution is appealing for modeling phenomena that undergo growth, stability and decline, which is characteristic of the different stages of technological diffusion in agricultural production.[12] Figure 3, Panel a illustrates the general case of the unit trapezoidal distribution. The first parameter of the distribution, $1 \geq a \geq 0$, captures the proportion of time from the initiation of benefits or costs until the maximum is achieved. The second parameter, $1 \geq b \geq 0$, captures the proportion of time that maximum benefits or costs are sustained. The difference $1 - a - b \geq 0$ captures the proportion of time with decreasing benefits or costs until they cease altogether, which occurs as new technical advances supplant previous ones or the (biological) technology loses effectiveness. Panels (b) – (d) illustrate the flexibility of this distribution in terms of capturing a variety of benefit or cost distributions. Panel b shows the parametric assumptions that yield the uniform distribution: $a = 0$ and $b = 1$. Panel c shows one of the many triangular distributions that can be represented: $1 \geq a \geq 0$ and $b = 0$. Panel d shows a characterization where benefits or costs are initially constant and then declining: $a = 0$ and $1 > b > 0$. Alternatively, for $a > 0$, $b > 0$, and $a + b = 1$, benefits or cost will initially be increasing and then constant. In addition to being quite flexible, the two-parameter, unit trapezoidal characterization of costs and benefits provides a parsimonious parameter space (i.e., two two-dimensional simplexes) that can be easily searched to find the distributions that come closest to

---

[11] The details of our reconstruction methodology are found in the Appendix.

[12] As Alston et al. (2008. p. 8) pointed out, in an empirical setting "The research lag coefficients will represent a hybrid of the effects of research on innovations, the uptake and depreciation of knowledge and technological innovations, and the consequences of the omission of the longer lags."

satisfying equation (3) (e.g., that minimizes the squared difference between the right- and left-hand side of the equation).

[Figure 3: *Examples of the two parameter unit trapezoidal distribution*]

The distributions of costs and benefits were approximated separately for each of the 302 evaluations that reported both the *IRR* and *BCR*. A relatively inefficient, but robust, grid search was used to find the parameters that minimized the squared difference in the observed and approximate *BCR*. There was a unique solution for all but two evaluations. For these two evaluations, the observed *BCR* equaled one implying an *IRR* equal to δ such that any distribution would yield a perfect approximation. For 79 percent of the remaining 300 evaluations, the observed *BCR* was within 0.1 percent of the approximated *BCR*. For 86 percent of the evaluations, the approximated *BCR* was within 5 percent of the observed value. A closer look at evaluations where the observed and approximate *BCR*s differed more substantially often revealed reasonable explanations. Some evaluations were aggregations of several others. Some were derived from multi-modal cost or benefit streams that cannot be closely approximated with the trapezoidal distribution. Since aggregated evaluations are inconsistent with the proposed methodology and multi-modal distributions are difficult to approximate with any parsimonious parametric distribution, we highlight both pooled and separate results for evaluations that have relatively small approximation errors (less than 5 percent) and those with larger approximation errors (more than 5 percent).

4. The Returns to Research Recalibrated

There were 431 R&D evaluations from 65 studies that reported a *BCR*. Assuming the reinvestment and cost of capital discount rates equal the discount rate used to compute these *BCR*s, equation (1) yields an average *MIRR* of 16 percent per year, with a minimum and

maximum of -100 percent per year and 128 percent per year respectively. The median *MIRR* is 14 percent per year, with an interquartile range of 14 percent per year (8 to 22 percent per year). With an average rate of return of 16 percent per year, a $4.1 billion investment in 2000 would generate $6.8 trillion (2005 U.S. dollars) worth of benefits in 2050, which is about nine orders of magnitude less than the value of the investment implied by the average *IRR* estimate for all studies that reported the *IRR*. The median *MIRR* would imply benefits of $2.9 trillion, which is five orders of magnitude smaller than what the median *IRR* for all studies implies.

Relaxing the assumption of equal discount rates for the 300 evaluations that also reported an *IRR* (that was not equal to the discount rate) and using the trapezoidal distribution to approximate the costs and benefits distributions, equation (2) can be used to explore the sensitivity of the *MIRR*s implied by these evaluations to alternative reinvestment and cost of capital discount rates. Figure 4, Panel a shows the results as the reinvestment rate varies from 0 to 10 percent per year and the cost of capital rate varies from 0 to 10 percent per year. The average *MIRR* is at a minimum of 11.7 percent per year in this range when the reinvestment and cost of capital rates are both 0 percent per year. It is at a maximum of 18.5 percent per year when the reinvestment and cost of capital rates are both 10 percent per year. This average is monotonically increasing in both the reinvestment and cost of capital rates. Therefore, for plausible assumptions regarding the reinvestment and cost of capital rates, the value of $4.1 billion investment in 2000 would yield benefits in the range of $1 trillion to $19.9 trillion by 2050. By comparison, the average *IRR* for the 300 studies in this subsample of evaluations is 52 percent per year, implying benefits of $5.1 quintillion by 2050. Figure 4, Panel b shows that the interquartile range varies relatively little between about 10 and 12 percent per year as the reinvestment and cost of capital rates are varied from 0 to 10 percent per year.

[Figure 4: Sensitivity of the modified internal rate of return to alternative
reinvestment and cost of capital rates]

We further explore the implications of recalibrating the *IRR* using the *MIRR* assuming a cost

of capital rate $\delta^c = 0.0296$ reflecting the average real rate of return for long-term U.S. treasuries

and a reinvestment rate $\delta^r = 0.035$ falling between the average rate of return to long-term U.S.

treasuries and Standard & Poor's 500 equity index from 1969 to 2010. [13] Two additional issues

we address that have been neglected in the literature, but are particularly relevant for publicly

funded R&D that generates privately accruing benefits, are the deadweight loss of taxation (e.g.,

Harberger 1964; Fox 1985) and the proportion of benefits that are consumed versus saved. With

a marginal excess burden (*MEB*) from taxation equal to $\delta^{MEB} \geq 0$ and a savings rate equal to $1 \geq$

$\delta^s \geq 0$, the *MIRR* in equation (2) can be rewritten as

$$(2') \quad MIRR = \sqrt[T]{BCR \frac{\sum_{t=0}^{T} w_{c_t}(1+\delta)^{-t}}{\sum_{t=0}^{T} w_{b_t}(1+\delta)^{-t}} \frac{\sum_{t=0}^{T} w_{b_t}\left((1-\delta^s)+\delta^s(1+\delta^r)^{T-t}\right)}{\sum_{t=0}^{T} w_{c_t}(1+\delta^{MEB})(1+\delta^c)^{-t}}} - 1$$

for real benefits and cost. Jones (2010) reviews estimates of the *MEB* from around the world

finding values ranging from 0.0 to 0.56 due to variation in methodologies, the types of taxes

evaluated, and the tax rates. For our purpose, we initially consider $\delta^{MEB} = 0.25$. To

approximate the proportion of benefits that are consumed and saved, we initially use the U.S.

private savings rate taken as a proportion of personal income from 1969 to 2010: $\delta^s = 0.045$.[14]

Figure 5 and Table 1 provide a detailed look at the reported *IRR*s and estimated *MIRR*s for

the subsample of 300 evaluations. Panel a in Figure 5 shows the rank ordered *IRR*s and the

corresponding *MIRR*s based on equation (1) assuming $\delta = \delta^r = \delta^c$. Panel b shows this same

comparison where the *MIRR*s are calculated based on equation (2'). Darker colored markers

---

[13] Data for the nominal rates of return of long-term U.S treasuries were obtained from James and Sylla (2006) and
BGFRS (2012). These data were inflation adjusted using the consumer price index obtained from BLS (2012).

[14] The data for this calculation was acquired from BEA (2012).

12

show results based on approximations with less than 5 percent error, while lighter colored markers show results of approximations with greater than 5 percent error. Table 1 reports descriptive statistics for the distributions of these estimates.

[Figure 5: *Comparison of the internal rate of return (IRR) to the modified internal rate of return (MIRR) under various assumptions*]

[Table 1: *Comparison of the internal rate of return (IRR) to the modified internal rate of return (MIRR)*]

The first notable result is that the *IRR* does not always exceed the *MIRR*. In particular, for relatively low values of the *IRR* the *MIRR* is larger, but this is true for less than 5.3 percent of the evaluations regardless of whether equation (1) or (2') is used in the calculation. For the vast majority of evaluations, the *MIRR* is lower with the difference tending to increase as the *IRR* gets larger. On average, the *IRR* is 3.5 times larger than the *MIRR* when equation (1) is used and 4.3 times larger when equation (2') is used for the calculation, which is even more dramatic than the 2.3 proportional difference found by Alston et al. (2011) for USDA and SAES R&D spending.

Comparing the subsample of 300 *IRR*s to the full sample of 2,077 *IRRs* using the two-sample Kolmogorov-Smirnov test, we can reject the equality of the distributions such that the probability of a smaller *IRR* is greater for the subsample (D = -0.1694, p-value < 0.000). Combining this result with the observation that the difference in *IRR* and *MIRR* tends to increase with the *IRR* then suggests that our estimate of this difference is low relative to what we would expect if we had enough information to reconstruct *MIRR*s for the full sample of evaluations. To get some sense of just how low, we regressed the *MIRR*s on the *IRR*s for the subsample (using a simple linear equation with an intercept) and then used these results to project *MIRR*s for the rest of the full sample. For *MIRR*s based on equation (1) with a regression R^2 of 0.59, the average *IRR* is estimated to be 4.0 times greater than the average *MIRR*. For *MIRR*s based on equation (2') with a regression $R^2 = 0.61$, the average *IRR* is estimated to be 5.1 times greater.

Comparing the *MIRR*s calculated based on equation (1), which did not rely on an approximation of the distributions of costs and benefits, to those calculated based on equation (2') for the subsample of 300 reveals that the means, medians, and 1st and 3rd quartiles are all modestly lower when using equation (2'). This result is attributable to the fact that the average discount rate used to evaluate the *BCR* in equation (1) was 5.1 percent per year, which is higher than both the reinvestment and cost of capital rates used in the calculations based on equation (2'). It is also attributable to our adjustment of costs to account for the marginal excess burden of taxation and benefits to account for the proportion that are reinvested. As the *MEB* in equation (2') is varied from 0 to 0.56 the average *MIRR* varies from 12.8 to 11.2 percent. Alternatively, varying the proportion of benefits reinvested in equation (2') from 0 to 0.5 results in variation in the average *MIRR* from 11.9 to 12.6 percent per year. Comparing the results based on equation (1) for the subsamples of 300 and 431 observations reveals relatively small differences—one to two percentage points. Together these results show the robustness of the *MIRR* estimates to alternative assumptions regarding the approximation methodology, the reinvestment and cost of capital rates, the *MEB* of taxation, and the proportion of reinvested benefits.

IRR and *MIRR* estimates for evaluations with a relatively high approximation error (greater than 5 percent) were lower on average than when the error was low (less than 5 percent) regardless of whether or not equation (1) or (2') is used to calculate the *MIRR*. This result suggests that the *MIRR* estimates are also fairly robust even with large approximation errors, since *MIRR* calculations based on equation (1) do not require approximations for the distributions of costs and benefits.

5. Conclusion

The plethora of estimates of returns to agricultural R&D investments that have emerged since Griliches' seminal evaluation of hybrid corn suggests these investments have paid off handsomely. Yet, contrary to what one might expect from this evidence, growth in agricultural R&D spending over the past five decades has ratcheted down in many countries—economists have failed to make their case to policy makers for the value of these investments. However, when considering the implications of the rates of return to agricultural R&D reported by economists over the past half a century and more, it is easy to understand why policy makers might be skeptical and choose to reject them.

The predominant measure of the rate of return to agricultural R&D investments used by economist during this period has been the internal rate of return (*IRR*). The *IRR* has prevailed even though it has been widely criticized, even by Griliches, for as long as it has been used as the summary statistic of choice in the agricultural R&D evaluation literature. We explore how the agricultural R&D rate of return evidence might have shaped up if economists had heeded Griliches' (and others) warnings and used some other summary measure of the returns to R&D. In particular, we explore the conceptually more appealing modified internal rate of return (*MIRR*). Using the *MIRR* to recast previous estimates of the *IRR*, we find much more muted returns to public agricultural R&D: a median of 12 versus 33 percent per year. With a return of 33 percent per year, the U.S.'s $4.1 billion investment in agricultural R&D in 2010 would generate $7 quintillion in benefits by 2050, which is 47 times larger than the world's projected GDP in 2050. With a 12 percent per year rate of return, this investment would produce $1.2 trillion, which is 4.2 percent of the U.S.'s projected GDP in 2050. Overall, we find that the

MIRR provides more muted, but also more plausible estimates for the rate of return to

agricultural R&D for a wide range of assumptions regarding important aspects of the calculation.

Our recalibrated estimates of the rates of return to public agricultural R&D are more modest

but still substantial compared with the opportunity cost of the funds used to finance the research.

This suggests society has persistently underinvested in public agricultural R&D, notwithstanding

the distorted view of the evidence created by reliance on the *IRR* to represent the returns to this

investment that has characterized the literature for the past 50 years. If this underinvestment

continues and the supply of important agricultural staples fails to keep pace with the growth in

aggregate demand, increasing food prices will further stress the world's most vulnerable

populations.

References

Alston, J.M., M.A. Andersen, J.S. James, and P.G. Pardey. "The Economic Returns to U.S. Public Agricultural Research." *American Journal of Agricultural Economics* 93(5)(2011): 1257-1277.

Alston, J.M., M.A. Andersen, J.S. James, and P.G. Pardey. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. New York: Springer, 2010.

Alston, J.M., B.A. Babcock and P.G. Pardey, eds. *The Shifting Patterns of Agricultural Production and Productivity Worldwide*, CARD-MATRIC on-line volume, Ames: Iowa State University, 2010. Available at www.matric.iastate.edu/shifting_patterns.

Alston, J.M., C. Chan-Kang, M.C. Marra, P.G. Pardey, and TJ Wyatt. *A Meta-Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem?* Research Report No. 113, Washington D.C.: International Food Policy Research Institute, 2000.

Alston, J.M., P.G. Pardey and V.W. Ruttan. "Research Lags Revisited: Concepts and Evidence from U.S. Agriculture." Department of Applied Economics Staff Paper No. P08-14, St Paul, University of Minnesota, December 2008.

Athanasopoulos, P.J. "A Note on the Modified Internal Rate of Return and Investment Criterion." *The Engineering Economist* 23(2)(1978): 131—133.

Baldwin, R.H. "How to Assess Investment Proposals." *Harvard Business Review* 37 (1959):98-104.

Biondi, Y. "The Double Emergence of the Modified Internal Rate of Return: The Neglected Financial Work of Duvillard (1755–1832) in a Comparative Perspective." *European Journal of the History of Economic Thought* 13(3)(2006): 311-335.

Board of Governors of the Federal Reserve System (BGFRS). Historical Data: Market Yield on U.S. Treasury Securities at 30-year Constant Maturity, Quoted on Investment Basis. Available at http://www.federalreserve.gov/releases/h15/data.htm on September 13, 2012.

Duvillard de Durand, E.-É. *Recherches sur les Rentes, les Emprunts et les Remboursemens* [*Researches on Rents, Loans and Repayments*]. Paris et Genève: Franç. Dufart Imprimeur-Libraire, 1718.

Evenson, R.E. "The Contribution of Agricultural Research to Production." *Journal of Farm Economics* 49(December 1967): 1415-1425.

Evenson, R.E. "Economic Impacts of Agricultural Research and Extension." Chapter 11 in B.L. Gardner and G.C. Rausser, eds. *Handbook of Agricultural Economics*, *Volume 1A: Agricultural Production*. New York: Elsevier, 2001.

FAO (Food and Agriculture Organization of the United Nations). "Hunger Statistics" on line. Rome: Food and Agriculture Organization of the United Nations, 2008. Retrieved August 2012 from http://www.fao.org/economic/ess/ess-fs/fs-data/ess-fadata/en/.

Foure, J., A. Benassy-Quere, and L. Fontagne. *The World Economy in 2050: A Tentative Picture*. CEPII Working paper 2010-27. Paris: French Center for Research and Studies on the World Economy, 2010.

Fox, G.C. "Is the United States Really Underinvesting in Agricultural Research?" *American Journal of Agricultural Economics* 67 (November 1985): 806–812.

Fuglie, K.O. and P.W. Heisey. *Economic Returns to Public Agricultural Research*. USDA, ERS Economic Brief No. 10. Washington D.C.: USDA, September 2007.

Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* 25(4)(1957): 501-522.

Griliches, Z. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." *Journal of Political Economy* 66(5)(1958): 419-431.

Harberger, A. "The Measurement of Waste." *American Economic Review* 54(3)(1964): 58-76.

Heckman, J. "Contributions of Zvi Griliches." NBER Working Paper 12318. Massachusetts: National Bureau of Economic Research, June 2006.

Hirshleifer, J. "On the Theory of Optimal Investment Decision." *Journal of Political Economy* 66(4)(1958): 329-352.

James, J.A., and R. Sylla, "Long-term Bond Yields: 1798–1997." Table Cj1192-1197 in S.B. Carter, S.S. Gartner, M.R. Haines, A.L. Olmstead, R. Sutch, and G. Wright, eds. *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, New York: Cambridge University Press, 2006.

Jones, C. "Interpreting and Using the Empirical Estimates of the MCF." Working Papers in Economics & Econometrics No. 519, Canberra: Australian National University. April, 2010.

Ivanic, M., and W.J. Martin. "Implications of Higher Global Food Prices for Poverty in Low-Income Countries." World Bank Policy Research Working Paper Series 4594. Washington, D.C.: The World Bank, 2008.

Lin, A.Y.S. "The Modified Internal Rate of Return and Investment Criterion." *The Engineering Economist* 21(4)(1976): 237 – 47.

Lorie, J. H., and L.J. Savage. "Three Problems in Rationing Capital." *The Journal of Business* 28(4)(1955): 229-239.

McMillen, W. *Too Many Farmers: The Story of What is Here and Ahead in Agriculture*. New York: William Morrow, 1929

Negrete, G.L. "The Modified Internal Rate of Return and Investment Criterion", A Reply. *The Engineering Economist* 23(2)(1978): 133—134.

Pardey, P.G., J.M. Alston and C. Chan Kang. "Agricultural Production, Productivity and R&D over the Past Half Century: An Emerging New World Order." Invited plenary paper presented at the International Association of Agricultural Economists (IAAE) Triennial Conference, Foz do Iguaçu, Brazil, September 14, 2012.

Ruttan, V.W. "Bureaucratic Productivity: The Case of Agricultural Research Revisited: A Rejoinder." *Public Choice*. 39(2)(1982): 319-329.

Ruttan, V.W. "Bureaucratic Productivity: The Case of Agricultural Research." *Public Choice* 35(5)(1980):529-547.

U.S. Bureau of Labor Statistics (BLS). Consumer Price Index: All Urban Consumers (CPI-U). Available at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt on September 13, 2012.

U.S. Department of Commerce Bureau of Economic Analysis (BEA). Comparison of Personal Saving in the National Income and Product Accounts (NIPAs) with Personal Saving in the Flow of Funds Accounts (FFAs). Available at http://www.bea.gov/national/nipaweb/Nipa-Frb.asp on September 13, 2012.

World Bank. National Accounts Data, and OECD National Accounts Data Files. Washington, D.C.: The World Bank, 2012. Available at http://data.worldbank.org/indicator/NY.GDP.MKTP.CD. Accessed July 7, 2012.

Appendix

The purpose of this appendix is to detail the methods used to estimate the modified internal rate of return (*MIRR*) from studies reporting only the cost and benefit terms of the investment, the internal rate of return (*IRR*), and the benefit-cost ratio (*BCR*) with its associated discount rate.

Let $t = 0,\ldots, T$ represent the overall term of the investment's costs and benefits. Let $c_t \geq 0$ and $b_t \geq 0$ represent the costs and benefits of the investment at time t. Define T_c as the point in time when costs cease to accrue such that $T \geq T_c > 0$ and T_b be the initial point in time when benefits start to accrue such that $T \geq T_b > 0$.

The net present value of costs (*NPC*) and benefits (*NPB*) given the discount rate δ are

(A1) $NPC = \sum_{t=0}^{T_c} c_t(1 + \delta)^{-t}$ and

(A2) $NPB = \sum_{t=T_b}^{T} b_t(1 + \delta)^{-t}$.

Let $C = \sum_{t=0}^{T_c} c_t$ be the aggregated costs (undiscounted) and $B = \sum_{t=T_b}^{T} b_t$ be the aggregated benefits (undiscounted). Rewrite equations (A1) and (A2) as

(A1') $NPC = C \sum_{t=0}^{T_c} w_{c_t}(1 + \delta)^{-t}$ and

(A2') $NPB = B \sum_{t=T_b}^{T} w_{b_t}(1 + \delta)^{-t}$

where $\boldsymbol{w_c} = \left(\frac{c_0}{C}, \ldots, \frac{c_{T_c}}{C}\right)$ is the distribution of costs and $\boldsymbol{w_b} = \left(\frac{b_{T_b}}{B}, \ldots, \frac{b_T}{C}\right)$ is the distribution of benefits.

The *BCR* is defined as

(A3) $BCR\left(\delta, \frac{B}{C}, \boldsymbol{w_c}, \boldsymbol{w_b}\right) = \frac{NPB}{NPC} = \frac{\sum_{t=T_b}^{T} b_t(1+\delta)^{T_0-t}}{\sum_{t=0}^{T_c} c_t(1+\delta)^{T_0-t}} = \frac{B}{C}\frac{\sum_{t=T_b}^{T} w_{b_t}(1+\delta)^{-t}}{\sum_{t=0}^{T_c} w_{c_t}(1+\delta)^{-t}}$,

which implies

(A4) $BCR\left(\delta, \frac{B}{C}, \boldsymbol{w_c}, \boldsymbol{w_b}\right)\frac{\sum_{t=0}^{T_c} w_{c_t}(1+\delta)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+\delta)^{-t}} = \frac{B}{C}$ and

(A5) $BCR\left(IRR, \frac{B}{C}, \boldsymbol{w_c}, \boldsymbol{w_b}\right) = 1.$

Equation (A5) further implies

(A6) $\frac{B}{C} = \frac{\sum_{t=0}^{Tc} w_{c_t}(1+IRR)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+IRR)^{-t}},$

which means equation (A3) can be written as

(A3') $BCR(\delta, IRR, \boldsymbol{w_c}, \boldsymbol{w_b}) = \frac{\sum_{t=T_b}^{T} w_{b_t}(1+\delta)^{-t}}{\sum_{t=0}^{Tc} w_{c_t}(1+\delta)^{-t}} \frac{\sum_{t=0}^{Tc} w_{c_t}(1+IRR)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+IRR)^{-t}}.$

Equation (A3') shows the relationship between the *BCR* and its associated discount rate, the *IRR*,

and the distributions of costs and benefits.

The *MIRR* can be defined as

(A7) $MIRR = \sqrt[T]{\frac{B}{C} \frac{\sum_{t=T_b}^{T} w_{b_t}(1+\delta^r)^{T-t}}{\sum_{t=0}^{Tc} w_{c_t}(1+\delta^c)^{-t}}} - 1$

where δ^r is the constant reinvestment discount rate and δ^c is the constant cost of capital discount

rate. If the reinvestment and cost of capital rates are the same as the *BCR*'s discount rate (i.e.,

$\delta = \delta^r = \delta^c$), there is a direct relationship between the *MIRR* and *BCR*:

(A8) $MIRR = (1+\delta)\sqrt[T]{BCR} - 1,$

a result that was noted by Athanasopoulos (1978) and Negrete (1978). If these rates are not the

same as the *BCR*'s discount rate, the relationship becomes more complicated. Substituting

equation (A4) into (A7) yields:

(A9) $MIRR = \sqrt[T]{BCR \frac{\sum_{t=0}^{Tc} w_{c_t}(1+\delta)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+\delta)^{-t}} \frac{\sum_{t=T_b}^{T} w_{b_t}(1+\delta^r)^{T-t}}{\sum_{t=0}^{Tc} w_{c_t}(1+\delta^c)^{-t}}} - 1.$

Equation (A9) says that the *MIRR* can in general be calculated directly from the *BCR* provided

all the discount rates are known and the distributions of costs and benefits are known. While the

discount rate associated with calculating the *BCR* is typically reported in previous studies and the

reinvestment and cost of capital rates are typically taken as exogenous, the distributions of cost

and benefits are not typically reported. However, equation (A3') suggests a strategy for

identifying reasonable approximations for these distributions using only reported information.

Let T^o be the observed investment term, $T_c{}^o$ be the observed ending date of investment

costs, $T_b{}^o$ be the observed initiation date of investment benefits, IRR^o be the observed IRR, BCR^o

be the observed BCR and δ^o be the observed discount rate associated with BCR^o. Equation (A3')

implies

(A3'') $\quad BCR^o = \dfrac{\sum_{t=T_b^o}^{T^O} w_{b_t}(1+\delta^o)^{-t}}{\sum_{t=0}^{T_c^O} w_{c_t}(1+\delta^o)^{-t}} \dfrac{\sum_{t=0}^{T_c^O} w_{c_t}(1+IRR^o)^{-t}}{\sum_{t=T_b^o}^{T^O} w_{b_t}(1+IRR^o)^{-t}}.$

Consider the density $f(x; \boldsymbol{\alpha})$ for $x \in [0, 1]$ where $\boldsymbol{\alpha}$ is some vector of parameters. Let $F(x; \boldsymbol{\alpha})$ be

the cumulative distribution function for $f(x; \boldsymbol{\alpha})$. Define

(A10) $\quad w_{c_t}(\boldsymbol{\alpha_c}) = F\left(\dfrac{t+1}{T_c^o+1}; \boldsymbol{\alpha_c}\right) - F\left(\dfrac{t}{T_c^o+1}; \boldsymbol{\alpha_c}\right)$ for $t = 0, \dots, T_c^o$ and

(A11) $\quad w_{b_t}(\boldsymbol{\alpha_b}) = F\left(\dfrac{t-T_b^o+1}{T^o-T_b^o+1}; \boldsymbol{\alpha_b}\right) - F\left(\dfrac{t-T_b^o}{T^o-T_b^o+1}; \boldsymbol{\alpha_b}\right)$ for $t = T_b^o, \dots, T^o$.

Equations (A10) and (A11) can be used with equation (A3') to approximate BCR^o:

(A12) $\quad BCR^o \approx BCR(\boldsymbol{\alpha_c}, \boldsymbol{\alpha_b}) = \dfrac{\sum_{t=T_b^o}^{T^O} w_{b_t}(\boldsymbol{\alpha_b})(1+\delta^o)^{-t}}{\sum_{t=0}^{T_c^O} w_{c_t}(\boldsymbol{\alpha_c})(1+\delta^o)^{-t}} \dfrac{\sum_{t=0}^{T_c^O} w_{c_t}(\boldsymbol{\alpha_c})(1+IRR^o)^{-t}}{\sum_{t=T_b^o}^{T^O} w_{b_t}(\boldsymbol{\alpha_b})(1+IRR^o)^{-t}}.$

Picking the "best" approximation can be accomplished by minimizing a chosen loss

function that depends on BCR^o and $BCR(\boldsymbol{\alpha_c}, \boldsymbol{\alpha_b})$ with respect to $\boldsymbol{\alpha_c}$ and $\boldsymbol{\alpha_b}$. The loss function

selected is the ubiquitous squared error function: $L = \left(BCR^o - BCR(\boldsymbol{\alpha_c}, \boldsymbol{\alpha_b})\right)^2$. To maintain

computational feasibility, the densities used to approximate the BCR were restricted to the two

parameter unit-trapezoidal class. Given the parameter estimates $\boldsymbol{\alpha_c^e}$ and $\boldsymbol{\alpha_b^e}$, the $MIRR$ was then

estimated as

$$(A9') \quad MIRR(\delta^c, \delta^r) = \sqrt[T]{BCR^o \frac{\sum_{t=0}^{T_c} w_{c_t}(\alpha_c^e)(1+\delta^o)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(\alpha_b^e)(1+\delta^o)^{-t}} \frac{\sum_{t=T_b}^{T} w_{b_t}(\alpha_b^e)(1+\delta^r)^{T-t}}{\sum_{t=0}^{T_c} w_{c_t}(\alpha_c^e)(1+\delta^c)^{-t}}} - 1,$$

which varies with the selection of the reinvestment and cost of capital discount rates.
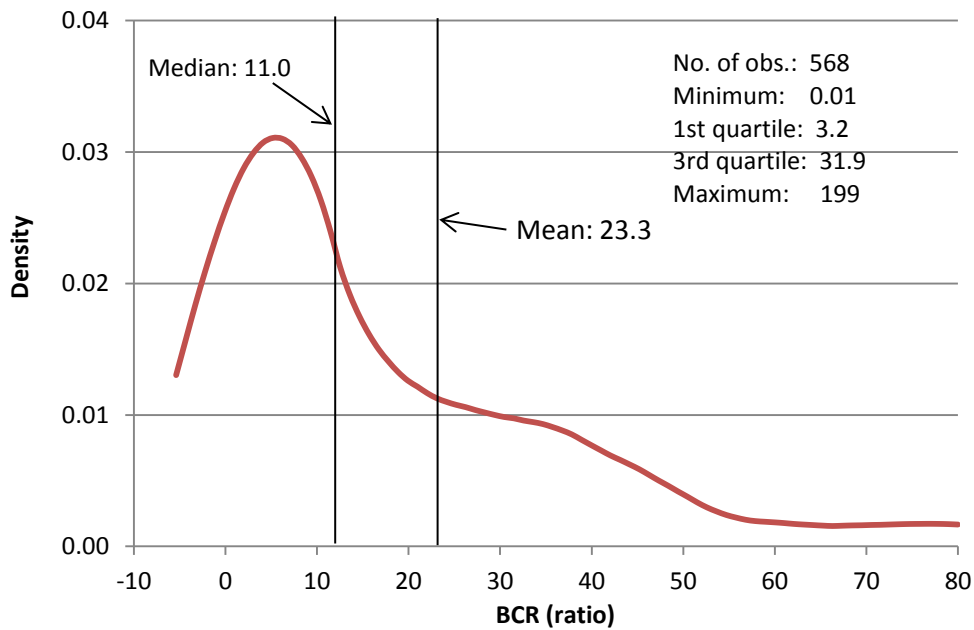
Figure 1: Distribution of reported internal rates of return estimates
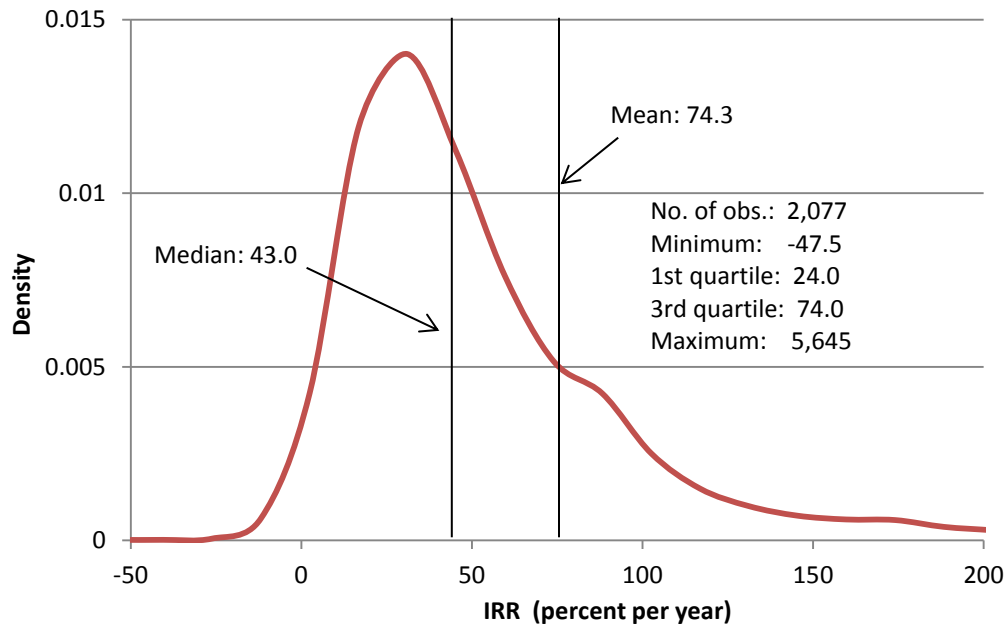
Source: Authors' compilation.

Notes: Plot represents a Kernel density estimate (kernel = epanechnikov, bandwidth = 6.2585) fitted across 2,077
IRR estimates. For presentation purposes the plotted observations were truncated at 200.

Figure 2: Distribution of reported benefit-cost ratio estimates

Source: Authors' compilation.

Notes: Plot represents a Kernel density estimate (kernel = epanechnikov, bandwidth = 4.5508) fitted across 568 BCR estimates. For presentation purposes the plotted observations were truncated at 80.

Figure 3: Examples of the two parameter unit trapezoidal distribution

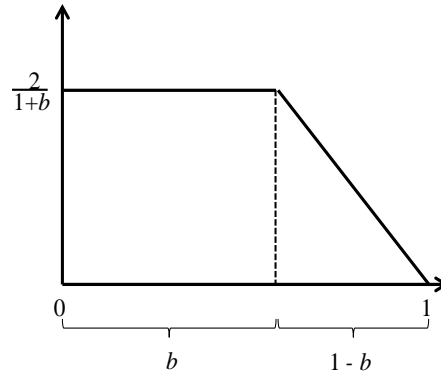Panel a: $1 \geq a \geq 0$, $1 \geq b \geq 0$, and $1 - a - b \geq 0$
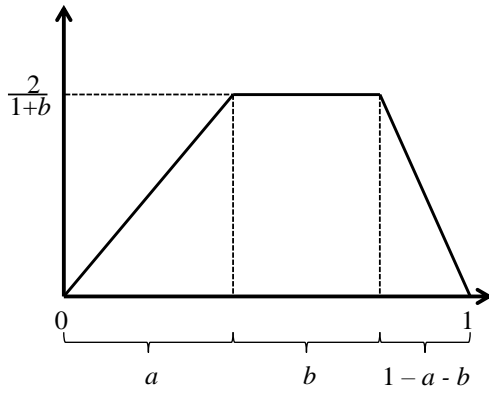
Panel b: $a = 0$ and $b = 1$
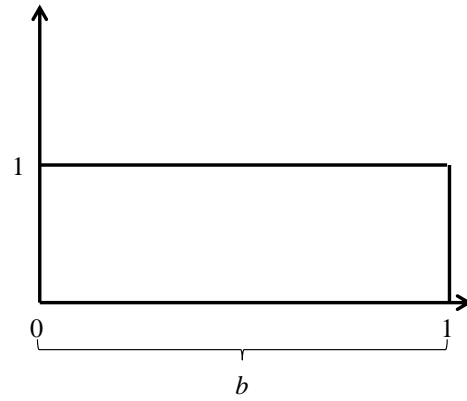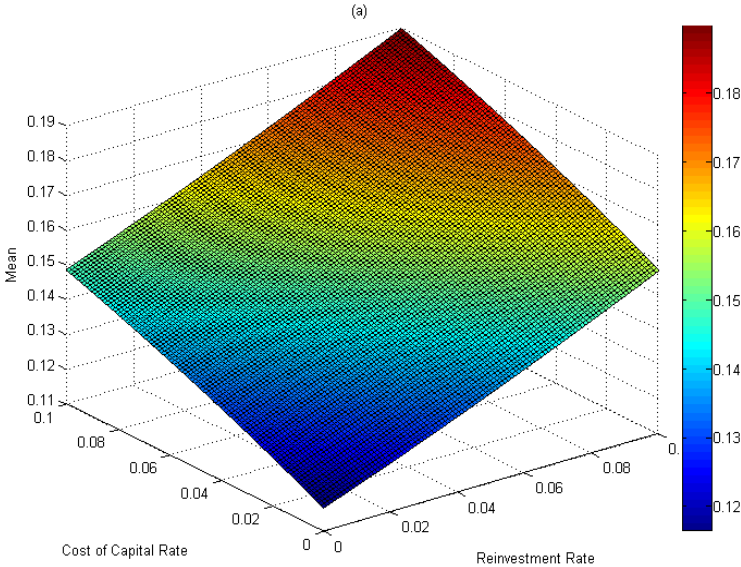

Panel c: $1 \geq a \geq 0$ and $b = 0$
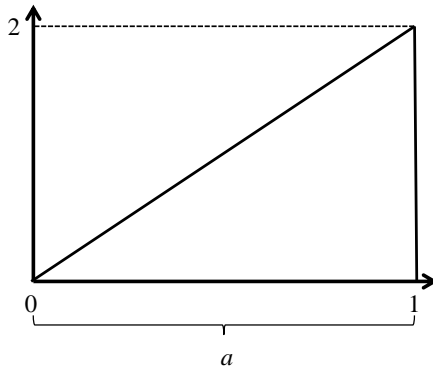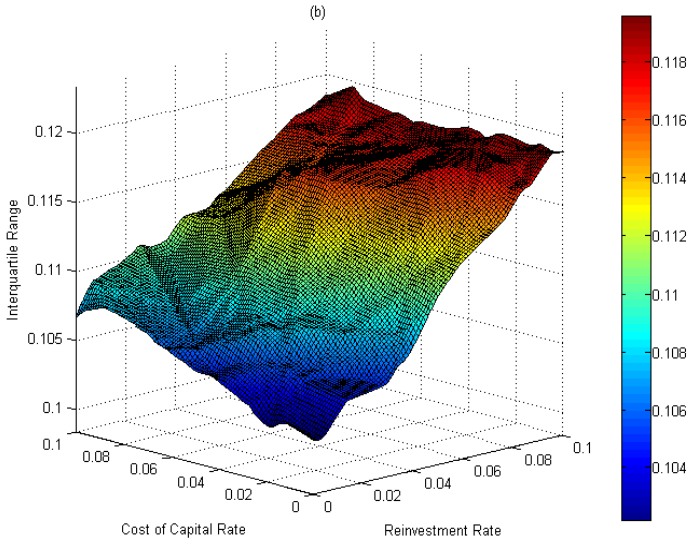
Panel d: $a = 0$ and $1 > b > 0$

Source: Authors' construction.

Figure 4: Sensitivity of the modified internal rate of return to alternative reinvestment and cost of capital rates.
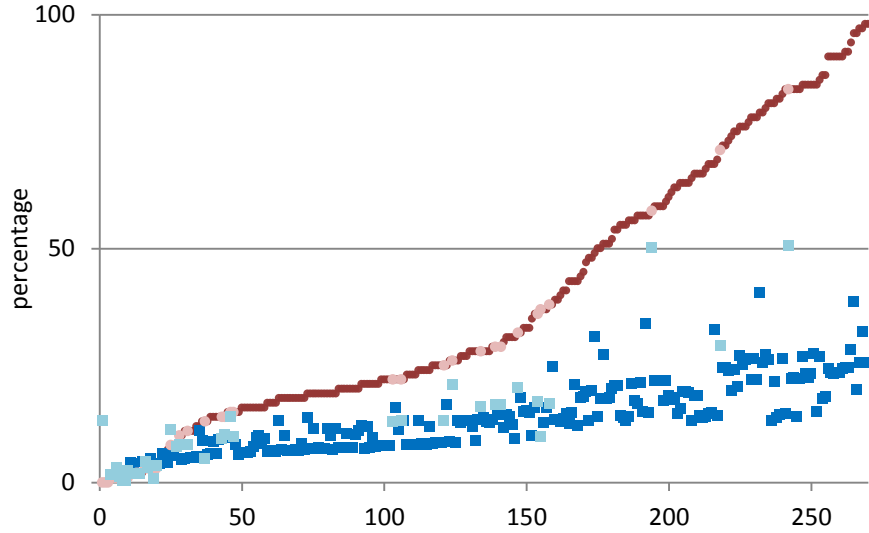
Panel a: Average modified internal rate of return

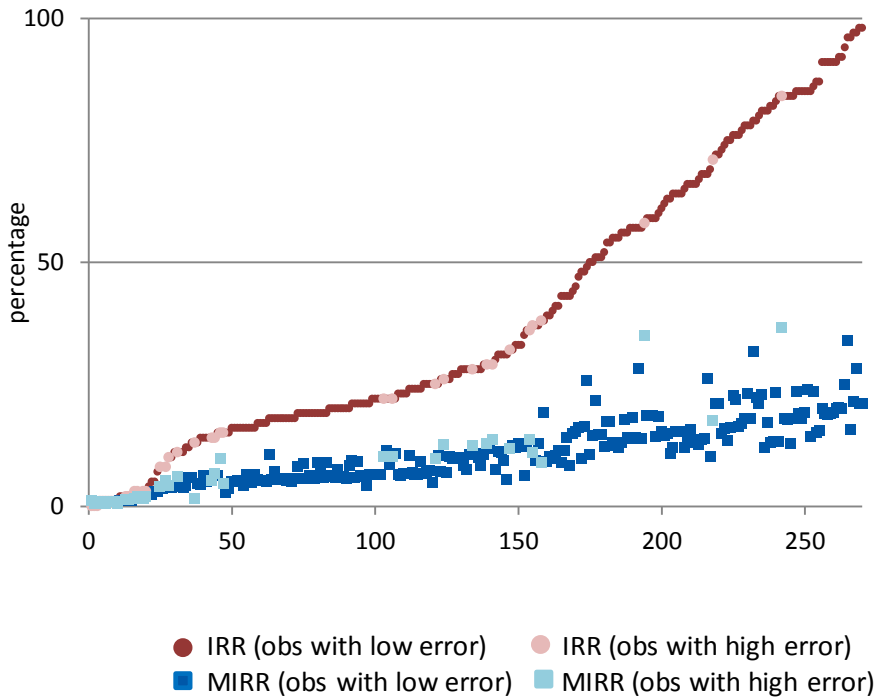Panel b: Interquartile range of modified internal rate of return

Source: Authors' estimates.

Figure 5: Comparison of the internal rate of return (*IRR*) to the modified internal rate of return (*MIRR*) under various assumptions

Panel a: *MIRR*, reinvestment and cost of capital rates are equal

Panel b: Reinvestment, cost of capital, and saving rates are 3.5, 3, and 4.5 percent per year respectively, plus marginal excess burden (MEB) of taxation of 25 percent.

IRR (obs with low error)   IRR (obs with high error)
MIRR (obs with low error)   MIRR (obs with high error)

Source: Authors' estimates.
Notes: For presentation purposes the plotted observations were truncated at 270.

Table 1: Comparison of the internal rate of return (IRR) to the modified internal rate of return (*MIRR*)

	Pooled	Low Error	High Error
Internal rate of return (IRR)			
No. of Obs.	300		
Mean	52		
Minimum	0		
1st Quartile	19		
Median	33		
3nd Quartile	76		
Maximum	677		
MIRR with $\delta^r = \delta^c = \delta$			
No. of Obs.	300	258	42
Mean	15	16	12
Minimum	-2	4	-2
1st Quartile	8	8	3
Median	14	14	10
3nd Quartile	21	22	17
Maximum	128	128	51
No. of Obs. with IRR<=MIRR (Weight of total sample)	16 (5.3%)	7 (2.7%)	9 (21.4%)
No. of Obs. with IRR>MIRR (Weight of total sample)	284 (94.7%)	251 (97.3%)	33 (78.6%)
MIRR with $\delta^r = 3.5\%$, $\delta^c = 3\%$, $\delta^s = 4.5\%$ and $\delta^{MEB} = 25\%$			
No. of Obs.	300	258	42
Mean	12	13	8
Minimum	0	1	0
1st Quartile	6	6	1
Median	11	12	5
3nd Quartile	16	17	12
Maximum	109	109	36
No. of Obs. with IRR<=MIRR (Weight of total sample)	3 (1%)	0 (0%)	3 (7.1%)
No. of Obs. with IRR>MIRR (Weight of total sample)	297 (99%)	258 (100%)	39 (92.9%)

Source: Authors' estimates.