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Improved Forages and Milk Production in East Africa

A case study in the series:

Economic foresight for understanding the role of investments in agriculture for the global food system

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Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture
Km 17 Recta Cali–Palmira CP 763537
P. O. Box 6713
Cali, Colombia
Phone: +57 2 4450000
Fax: +57 2 4450073
Website: www.ciat.cgiar.org
E-mail: s.prager@cgiar.org

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Carlos González is a research assistant in CIAT's Decision and Policy Analysis (DAPA) Research Area at headquarters in Cali, Colombia. Economist specializing in regional economics and spatial analysis of economic activity.

Ben Schiek is a research associate in CIAT's DAPA Research Area at HQ in Colombia. Applied economist specializing in ex ante impact assessment and the evaluation of tradeoffs in agricultural systems.

Solomon Mwendia is a post-doctoral scientist with CIAT's Tropical Forages team at the Regional Office in Nairobi, Kenya. Agronomist specializing in the development and distribution of forage technology.

Steven D. Prager is a senior scientist in CIAT's DAPA Research Area at HQ in Colombia. Integrated modeler specializing in the application of strategic foresight and decision support for agricultural systems.

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Keywords: Tropical forages, forage technologies, ex ante impact assessment, economic surplus model.

Cover photo: Climate-smart brachiaria (Georgina Smith/CIAT).

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Executive Summary

Production of livestock and dairy products in Sub-Saharan Africa has not kept pace with growing demand. The potential exists to close this gap in a climate-friendly way through the introduction of improved forage varieties of the *Brachiaria* genus. We assess the potential economic impact of the development and release of such varieties in six East African countries using an economic surplus model. Results are presented across a range of potential scenarios involving different adoption rates and percentage increases in productivity. For all but the lowest levels of adoption and productivity increases, improved forages have the potential for positive return on investment. Using these results, we present formulae that help readers calculate the adoption rate or percentage increase in productivity necessary to achieve specific desired levels of net benefit. Overall, the model output suggests that investment in a forages research program related to both the qualities of the forage itself as well as programs to enhance dissemination and adoption of new materials would be low risk and with high likelihood for positive outcome, generating discounted net benefits on the order of potentially tens of millions of dollars.

1. Introduction

Demand for livestock products in Sub-Saharan Africa has been increasing and is projected to continue increasing due to population growth, rising incomes, and urbanization (FAO, 2009; Ghimire et al., 2015; Robinson & Pozzi, 2011). Supply has not kept pace with these demands, due primarily to low productivity (Rakotoarisoa, Iafrate, & Paschali, 2011). The development challenges posed by the drivers behind these trends are further complicated by climate change (Thornton, 2010; Thornton et al., 2007). One of the major factors behind the region's chronic low productivity is a lack of quality feed options with high nutrient content. Producers in mixed, rainfed crop-livestock systems are particularly constrained by a shortage of feed resources during dry seasons; this condition is increasingly aggravated by pressures arising from climate change and variability (Dzowela, 1990; Rakotoarisoa et al., 2011; Thornton, 2010).

Experts agree that better use of the natural resource base offers tremendous potential to increase livestock productivity in the region (FAO, 2009; Ghimire et al., 2015). Research programs such as Climate Smart Brachiaria have begun developing climate-friendly strategies to tap into this potential (Djikeng et al., 2014). Such efforts are built around the development of drought resistant *Brachiaria* forage varieties with climate change-mitigating properties (Ghimire et al., 2015; Maass et al., 2015). In this study we present an ex-ante assessment of the potential welfare impacts of introducing such technology in East Africa, using an economic surplus method previously described by Alston et al. (1995).

1.1 Study area and scope

The geographic focus of this study is Kenya, Tanzania, Ethiopia, Uganda, Rwanda, and Burundi. In order to develop estimates for potential rates of forage technology adoption, production systems are classified according to the Seré and Steinfeld scheme (Robinson et al., 2011). There are thirteen system categories in the Seré and Steinfeld scheme, but we only consider the six categories that have a significant areal presence and cattle population size in the study zone (Figure 1).[1]

[1] The seven omitted categories are the three mixed irrigated (MI-) systems, the two hyper-arid (-Y) systems, and the urban and "other" categories.

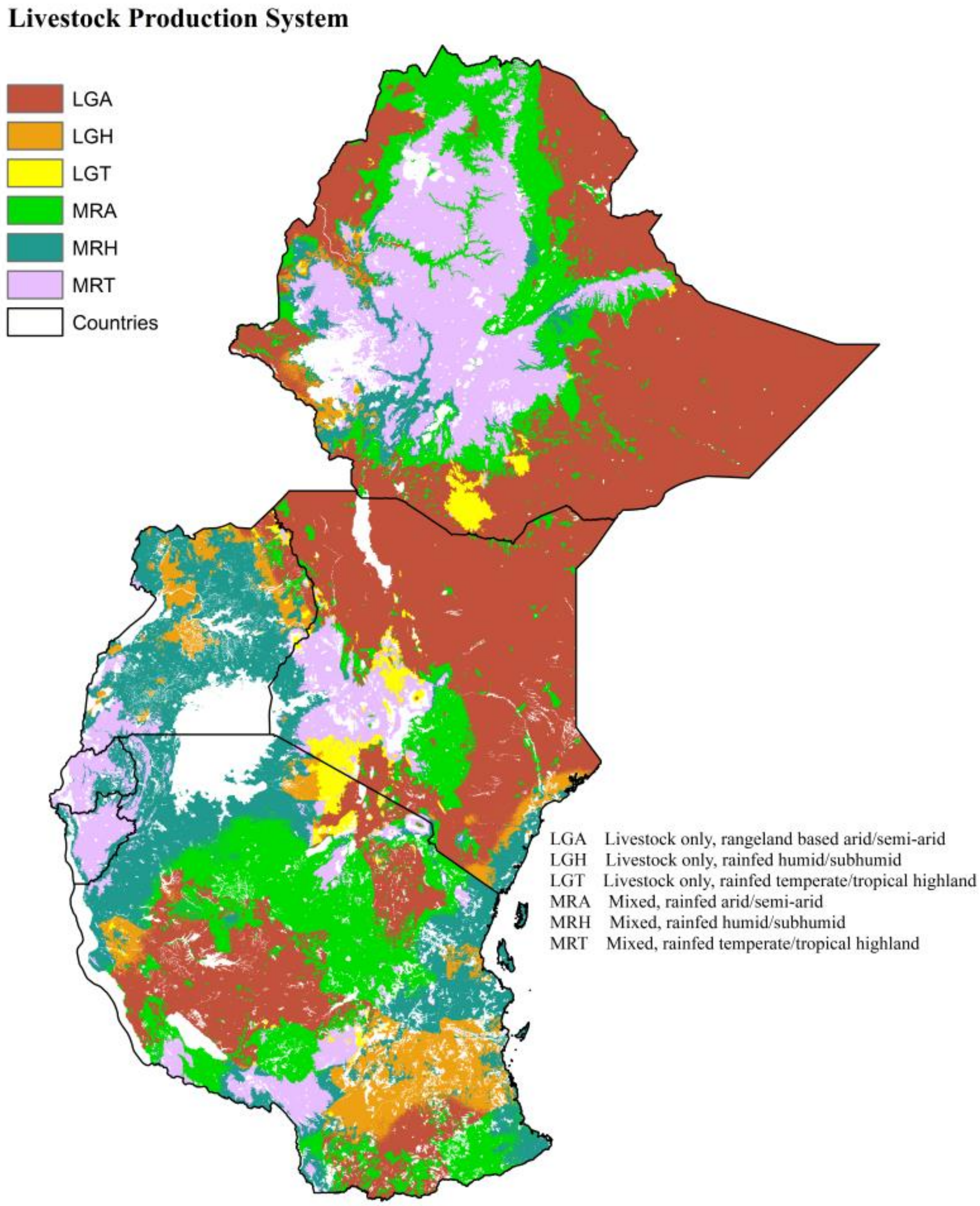


Figure 1: Production systems map of the study area.
Source: Authors' creation using data documented by Robinson et al. (2011).

In East Africa, dry season feed shortages have been of particular concern in mixed, rainfed crop-livestock systems (MRA, MRH, and MRT). These are the systems in which smallholder producers have the greatest potential to benefit from the introduction of improved forage varieties. Cattle density tends to be greatest in these areas (see Figure 2). Human population density is also substantial in these areas, while farm sizes tend to be small.

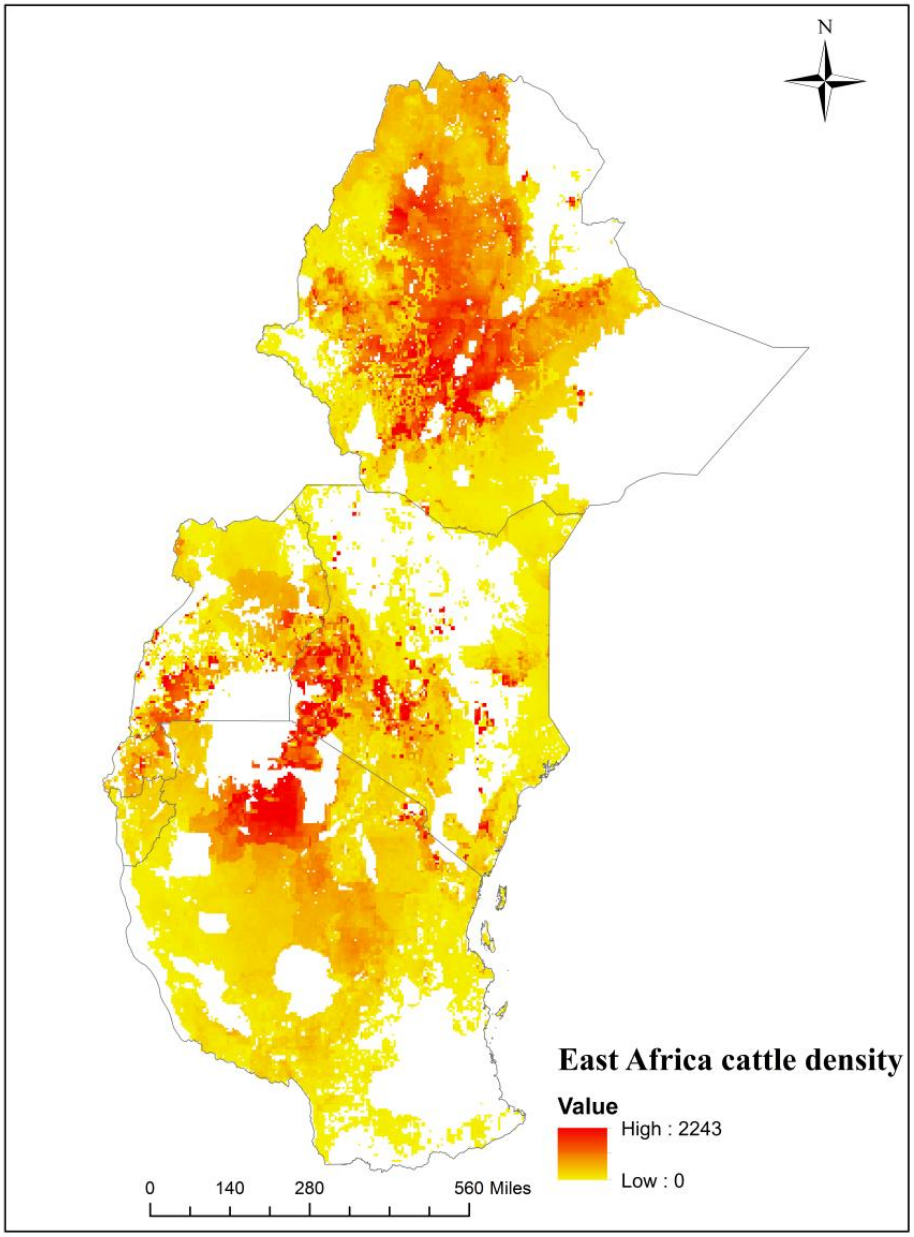


Figure 2: Cattle density map of the study area.
Source: Authors' creation using data documented by Robinson et al. (2014)

Many farms are less than the minimum size required to support a cow and its calf, which leads to the inference that a substantial proportion of production in these areas relies on cut-and-carry.

Our calculation of the percentage of national territory covered by each production system is presented in Table 1, and our estimate of the percentages of the national milk cow population present in each production system is presented in Table 2. A comparison of these two tables reveals that, although mixed rainfed systems cover a small area relative to rangeland (LG) systems, they are the basis for the majority of milk production.

Table 1: Percentage of national area corresponding to each production system

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	66.10%	23.6%	45.2%	5.3%	0.0%	0.0%
LGH	2.20%	10.4%	1.4%	15.2%	0.0%	0.0%
LGT	3.40%	1.6%	1.4%	1.2%	0.0%	0.0%
LG Subtotal	**71.70%**	**35.60%**	**48.00%**	**21.70%**	**0.00%**	**0.00%**
MRA	9.40%	27.3%	17.9%	1.8%	0.0%	0.0%
MRH	4.70%	22.2%	4.8%	58.2%	31.6%	23.6%
MRT	9.20%	6.2%	25.1%	7.2%	58.4%	68.9%
MR Subtotal	**23.30%**	**55.70%**	**47.80%**	**67.20%**	**90.00%**	**92.50%**
Total*	95.00%	91.30%	95.80%	88.90%	90.00%	92.50%

*The columns do not add up to exactly 100% because production system categories with a small areal presence are excluded from the study.

Table 2: Percentage of milk cows in each system

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	24.12%	5.62%	5.66%	1.47%	0.00%	0.00%
LGH	1.17%	2.32%	0.15%	7.99%	0.00%	0.00%
LGT	3.27%	0.15%	0.34%	0.56%	0.00%	0.00%
LG Subtotal	**28.56%**	**8.09%**	**6.15%**	**10.02%**	**0.00%**	**0.00%**
MRA	11.42%	34.82%	17.83%	0.60%	0.00%	0.00%
MRH	12.89%	36.03%	3.45%	59.02%	18.92%	7.49%
MRT	39.06%	9.14%	66.94%	9.18%	69.68%	56.17%
MR Subtotal	**63.37%**	**79.99%**	**88.23%**	**68.80%**	**88.60%**	**63.66%**
Total*	91.94%	88.08%	94.38%	78.82%	88.60%	63.66%

*The columns do not add up to 100% because production systems with a small areal presence are excluded from the study.

Current milk cow population data for the countries in this study is readily available only at the national level. The method by which we calculated the system-level disaggregation is explained in detail in section 3.

2. *Brachiaria* technology and milk production

The genus *Brachiaria*, of the grass family, consists of roughly 100 species which grow in the tropics and subtropics. Most of these species are native to Africa, where they constitute important components of the natural savannah landscape (Ghimire et al. 2015). Outside of Africa, widespread commercial adaptation and adoption of *Brachiaria* species in non-native environments has enhanced livestock industries worldwide — notably in Latin America and the Caribbean, as well as in Asia and Australia — and has made *Brachiaria* the most extensively cultivated forage monoculture in the world (Ghimire et al., 2015; Jank, Barrios, do Valle, Simeão, & Alves, 2014).

Generally speaking, the widespread appeal of *Brachiaria* lies in its adaptability to low quality, acidic soils along with its resistance to drought, shade, flooding, and its palatability. From an environmental perspective, it is also appealing because it transfers carbon from the atmosphere into the soil, makes efficient use of nitrogen, and helps to minimize groundwater pollution (Fisher et al., 1994; Fisher & Kerridge, 1996; Rao, 2014; Rao, Kerridge, & Macedo, 1996; Subbarao et al., 2009).

The success of *Brachiaria* in other parts of the world has motivated concerted efforts to introduce higher performance, improved cultivars in Africa. The same *Brachiaria* hybrids developed at CIAT over the course of the 1980s and 1990s for release in the Americas (Mulato and Mulato II) have been introduced in several African countries on an experimental basis since 2001. Limited uptake and diffusion of these hybrids has occurred through farmer-to-farmer transfer of planting material promoted by research programs. Much of this diffusion has been associated with the spread of "climate adapted push-pull" farming systems (Midega et al., 2015). Based on seed sales, it has been estimated that, as of 2014, some 3,000 hectares of these hybrids were under cultivation in various African countries, primarily in East Africa (Maass et al., 2015).

While initial results have shown some promise (Ghimire et al., 2015; Kabirizi, Ziiwa, Mugerwa, Ndikumana, & Nanyennya, 2013), these hybrids were developed specifically in response to biotic and abiotic stresses in Latin America. Their introduction in Africa has encountered biotic challenges which must be overcome before adoption and diffusion can be significantly scaled up (Maass et al., 2015).

A Swedish funded program called "Climate-smart Brachiaria Grasses for Improving Livestock Production in East Africa" (CSB) is addressing these challenges (Djikeng et al., 2014; Ghimire et al., 2015). The program is led by the Biosciences Eastern and Central Africa-International Livestock Research Institute Hub, and is in partnership with the Kenyan Agricultural and Livestock Research Organization, the Rwanda Agricultural Board, CIAT, and Grasslanz Technology Limited. The program is currently implemented in Kenya and Rwanda, with plans to expand both in East Africa and beyond.

In advance of the CSB program, ten *Brachiaria* cultivars—mostly from the *brizantha* species, but also including the hybrids Mulato and Mulato II—were tested in green houses at CIAT in Colombia against East African baseline varieties. Results were encouraging and, beginning in 2013, eight of these ten cultivars were selected for field trials at multiple sites in Kenya and Rwanda. Of these eight, *B. brizantha* cultivars Piatá, Marandu, La Libertad (also known as MG-4), Toledo (also known as Xaraes), the *B. decumbens* cultivar Basilisk, and the hybrid Mulato II emerged as the best performing varieties. Mulato II and Marandu were subsequently removed from this list after they proved susceptible to local pest infestation. On-farm evaluation of the remaining four cultivars began in 2014 and is ongoing at the time of this study (Climate Smart Brachiaria Program, 2016; Ghimire et al., 2015).

Preliminary data from recent trials indicates that adoption of these mostly *B. brizantha* cultivars has increased baseline milk production of 3-5 liters/cow/day on participating farms by 15%-40% in Kenya and by an average of 36% in Rwanda. In a special feeding experiment conducted in Rwanda, it has also been found that cows fed these cultivars gain weight faster than the baseline, resulting in increased meat production (Ghimire et al., 2015).

Brachiaria grasses are drought resistant and resilient in low quality soils, and do well with relative low levels of fertilizer inputs. They are also resistant to many diseases affecting baseline varieties in East Africa, particularly Napier stunt and smut disease (Ghimire et al., 2015; Maass et al., 2015). *Brachiaria* production can be further enhanced by intercropping with legumes (Kabirizi et al., 2013) which themselves are useful sources nutrition for both humans and animals.

Though *Brachiaria* forage dry matter yields are lower than those of baseline varieties, their leaf areas are relatively larger, effectively increasing palatability and nutrition per unit dry matter weight (Ooko, 2015). The protein content of *Brachiaria*, which is 8-17% at harvest, remains stable for a relatively long time as compared to that of baseline varieties, which diminishes after about four months (Climate Smart Brachiaria Program, 2016; Ooko, 2015). Surplus *Brachiaria* not immediately consumed can be dried and conserved as hay for sale or future use. This is not possible with baseline varieties, which must instead be stored as green silage—a relatively expensive, labor intensive process (Ooko, 2015).

The advantages and disadvantages of improved *Brachiaria* grasses relative to baseline varieties appear to vary seasonally. While *Brachiaria* outperforms baseline varieties during dry seasons, the baseline varieties exhibit certain advantages during rainy seasons (Kabirizi et al., 2013). On many farms, it may make sense to introduce the improved

Brachiaria grasses as a dry season complement to the baseline grasses. Kabirizi et al. (2013) point out that small farms which introduce *Brachiaria* in such a complementary role would probably have to displace a cash crop in order to make room for the new addition, and may thus incur cost in terms of forgone revenue.

As of May 2016, at least 4,000 farmers in Kenya and Rwanda have planted one of the *Brachiaria* cultivars under CSB evaluation (Climate Smart Brachiaria Program, 2016). Experts at CIAT report that participating farmers appear to prefer the *B. brizantha* Piatá cultivar out of the four cultivars that are currently under CSB evaluation (J. A. Cardoso, email correspondence, April 12, 2016).

3. Materials and methods

In order to estimate the economic benefit for each country in the study area, we calculate the net present value (NPV) of the cost-benefit stream extending from the year of initiation of research until the adoption ceiling is reached. Country level costs occur in the form of diffusion costs during the first several years of adoption. The program level net present benefit is defined as the sum of these country level NPVs minus the research cost stream.

Benefits are calculated using the economic surplus model for closed economies as set forth by Alston et al. (1995), and can be defined in terms of producer surplus, consumer surplus, or total surplus (see Appendix A.1 for mathematical details). In this study, the primary beneficiaries of the new technology are smallholder producers, and so benefits should be calculated on a producer surplus basis. Nonetheless, results are also presented on a total surplus and consumer surplus basis should the reader be interested in examining consumer side impacts.

3.1 Research period and diffusion costs

Program level costs accrue in the form of research costs, while diffusion costs are incurred at the country level. A forage breeding expert consulted for this study suggested that the research period (T_r) could last about 10 years and cost \$1.5 million per year (M. Peters, email correspondence, May 3, 2016). We assume, then, that release and uptake of the new technology begin in year 11.

We also assume that country-level diffusion efforts last for eight years. We model a given country's diffusion cost as a marginally diminishing function of the size of its target dairy industry, where target industry size is measured by the number of milk cows in the country's mixed, rainfed crop-livestock systems. More specifically, we set this cost to be equal to USD \$0.10 per milk cow, and set the percentage increase in cost for every 1% increase in industry size to 0.97% (see Appendix A.3 for details). These parameter settings are chosen because they generate diffusion cost magnitudes commensurate with the types of promotional, capacitation, and outreach activities that are typical of program level diffusion efforts (Table 3). While these values are certainly debatable, the results of this study are not sensitive to them.

Table 3: Diffusion cost per year (USD)

Duration of diffusion efforts: 8 years
Diffusion cost per cow: $0.10
% increase in cost per 1% increase in industry size: 0.97%

	Diffusion cost/yr.	Target industry size (number of milk cows in MR systems)
Kenya	$231,198.66	3169616
Tanzania	$348,876.53	5519334
Ethiopia	$593,648.65	9419634
Uganda	$152,807.48	2339196
Rwanda	$17,327.86	250127
Burundi	$5,451.61	55316

Note: Target industry size imputed based on country-level milk cow population size data from FAOSTAT averaged over 2009-2013 (2016c). See sections 3.4 and A.4 for imputation methodology.

3.2 Producer prices

In order to obtain the producer milk prices required by the economic surplus model we consulted both FAOSTAT and local field experts. Neither of these two sources on their own offered complete price data for all the countries involved in this study; but together they provide a mostly complete picture.

FAOSTAT reports recent producer milk prices for Kenya, Ethiopia, and Rwanda. For these countries, we used the average over 2010-2012, which is the most recent consecutive period for which FAOSTAT reports price data for all three countries.

Field experts provided price data for Tanzania, Ethiopia, Uganda, and Rwanda. In order to be consistent with the FAOSTAT prices, we again use the 2010-2012 average for these countries, except Uganda. Our Uganda respondent only reported prices for the years 2013-2015; and so the Uganda producer milk price is averaged over this period.

Our respondents reported prices in local currency per kilogram. We converted these prices to USD per metric ton using historical exchange rates retrieved for June 15th of each respective year.

For Rwanda and Ethiopia, we have price data from both FAOSTAT and field experts. In these cases we use the lesser of the two prices. No price data could be obtained for Burundi from any source. We set Burundi's producer price equivalent to that found in Rwanda.

Table 4: Producer milk prices (USD/metric ton)			
	Producer price	**Averaged over**	**Source**
Kenya	$314.8	2010-2012	FAOSTAT
Tanzania	$369.5	2010-2012	Field expert
Ethiopia	$481.3	2010-2012	FAOSTAT
Uganda	$358.1	2013-2015	Field expert
Rwanda	$338.6	2010-2012	Field expert
Burundi	$338.6	2010-2012	No data (Rwanda price)

Note: Authors' calculations using input from field experts and Faostat (2016b).

3.3 Change in productivity and variable cost

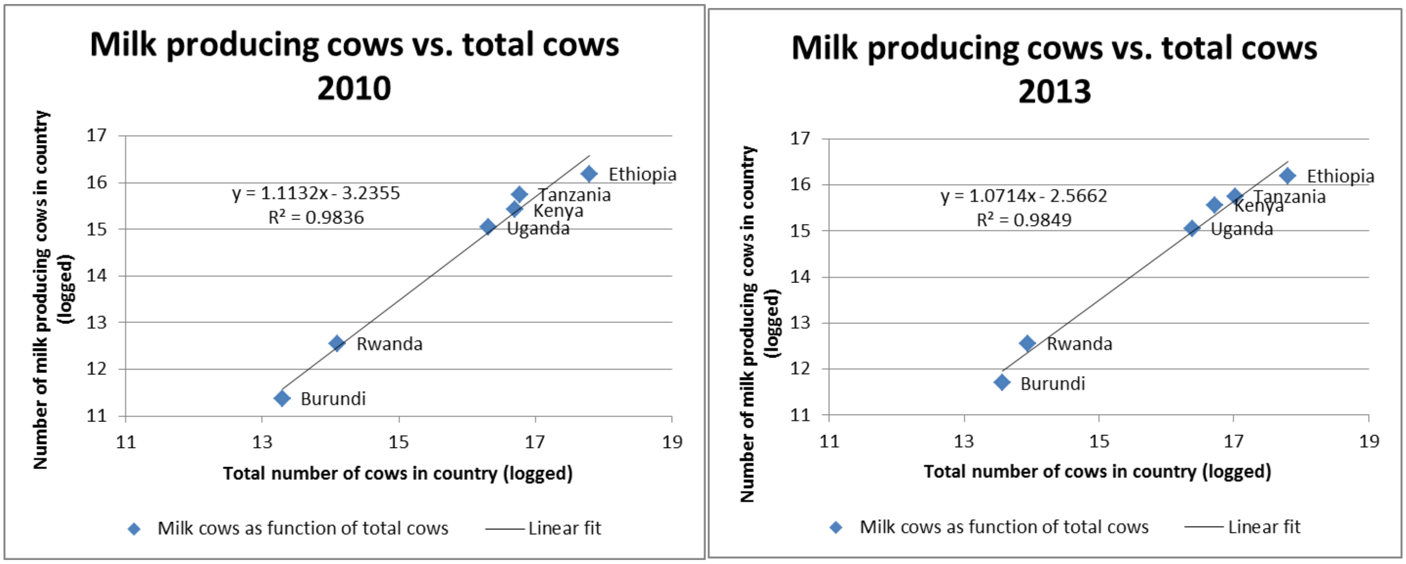
As discussed in section 2, preliminary data suggest that adoption of the new technology can increase cow milk productivity ($E[y]$) by 15-40%. For the sake of expedience and parsimony, we focus only on milk production, and do not attempt to model other associated benefits and nuances mentioned in section 2 (increased meat production, push pull systems, value of mitigation, and enhanced production via leguminous intercropping).

The improved varieties require less fertilizer, implying a decrease in variable cost associated with the new technology. However, as mentioned in section 2, smallholder farmers who introduce the new technology in a complementary role would probably have to displace a cash crop, and thus incur a cost in the form of forgone revenue. At an aggregate level, this would offset welfare gains from the variable cost reduction to some extent, although it is unclear by how much. In an attempt to balance these considerations, we have set the percentage change in variable costs ($E[C]$) to 0%.

3.4 Quantity of production affected

The quantity of production affected by the new technology (Q) is just the baseline production already occurring in areas where the new technology is likely to appeal to producers. The *Brachiaria* varieties under evaluation in the CSB program are expected to appeal primarily to producers in mixed, rainfed crop-livestock systems, where baseline varieties currently fail to generate a sufficient feed supply during dry seasons.

Recent milk production data for the countries in this study is currently only available at the national level. In order to estimate milk production within individual production systems, we first overlaid FAO's 2010 cattle density map (Figure 2), onto the production system map (Figure 1) and counted the cattle within each production system (Robinson et al., 2014). In order to impute how many of these cattle were milk producing cows, we specified the model based on an observed empirical functional relationship between total cattle and milk producing cattle in the FAOSTAT country level data (Figures 3 and 4).



Figures 3 and 4: Number of milk cows plotted against total cattle for each of the countries in this study for 2010 and 2013. Authors' creation using data from FAOSTAT (2016c, 2016a).

The starting model specification rests upon the hypothesis that the empirical relation observed at the country level is scale invariant, and will thus be observed at sub-national levels of disaggregation (district, village, production system, etc.). We cannot test this hypothesis directly because we do not have disaggregated data. However, we do have enough data to test one important necessary (if not sufficient) condition for the hypothesis to be true: If the hypothesis is true, then 1) the imputed numbers of milk cows at the production system-level must add up to the country level milk cow total reported by FAOSTAT, and 2) the parameter values of the function used to impute these system-level numbers should be very close to the parameter values that were fitted at the country level using FAOSTAT data in Figures 3 and 4.

When we fit the system-level parameters for each country such that the respective sums are equal to the 2010 FAOSTAT country level totals, we indeed find that the parameter values are close to the country-level values. The results of this imputation, including the fitted parameter values, are included in Table 13 of section A.4 of the Appendix.

The system-level milk cow numbers imputed using this model are valid only for 2010, since that is the year of the cattle density map data used to fit the parameters. In order to disaggregate milk cow population sizes to the system level for any year, we calculated each system's 2010 milk cow population as a percentage of the 2010 country-level milk cow population. These are the system-level percentages shown earlier in Table 2. Assuming that these percentages change little over time (e.g., a decade), we could then deduce the milk cow population size in any production system of a given country for any given year (within, say, a decade of 2010), by multiplying the milk cow percentages in Table 2 by the national milk cow population size reported by FAOSTAT for the country and year of interest. The most recent year for which FAOSTAT reports country-level milk cow population size for the countries in this study is 2013. As an additional conservative measure, we multiplied the percentages in Table 2 by a five year average (2009-2013) instead of focusing on a single year (FAOSTAT, 2016c). The results of this calculation for the production systems examined in this study are displayed in Table 5. The industry size figures used in the calculation of diffusion costs in section 3.1 are taken from this Table.

Table 5: Milk cows disaggregated by production system (imputed)

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	1356761.6	387400.4	594347.4	49973.1	0.0	0.0
LGH	66001.4	159775.9	15629.5	271777.7	0.0	0.0
LGT	183734.5	10033.7	35808.5	19035.7	0.0	0.0
LG Subtotal	**1606497.5**	**557209.9**	**645785.3**	**340786.5**	**0.0**	**0.0**
MRA	642276.7	2398932.1	1872406.9	20518.6	0.0	0.0
MRH	725105.9	2482741.2	362433.0	2006596.5	53469.7	7383.9
MRT	2196712.8	629663.1	7027729.7	312081.0	196927.4	55367.5
MR Subtotal	**3564095.4**	**5511336.3**	**9262569.5**	**2339196.2**	**250397.1**	**62751.4**
Total	5170592.9	6068546.3	9908354.9	2679982.7	250397.1	62751.4

In order to estimate system-level milk production, we multiplied the percentages in Table 2 by the 2009-2013 average milk production (Table 6). In doing so, we gloss over important heterogeneity in milk yields from one production system to another. This necessary simplification is an unavoidable consequence of the data limitations. The production affected by the new technology in each country (Q) is then just the sum of milk production in the MRA, MRH, and MRT systems in Table 6.

Table 6: Milk production disaggregated by production system (imputed, metric tons)

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	904655.73	108047.04	226444.82	17747.78	0.00	0.00
LGH	44008.13	44561.93	5954.79	96521.06	0.00	0.00
LGT	122509.69	2798.42	13642.94	6760.49	0.00	0.00
LG Subtotal	**1051187.6**	**141808.0**	**223075.2**	**119275.3**	**0.0**	**0.0**
MRA	428254.48	669068.77	713382.18	7287.13	0.00	0.00
MRH	483483.03	692443.36	138086.03	712636.85	35570.37	3077.45
MRT	1464714.77	175614.78	2677546.81	110834.65	131004.73	23075.95
MR Subtotal (Q)	**2376452.28**	**1537126.90**	**3529015.02**	**830758.63**	**166575.10**	**26153.40**
Total	3383300.1	1544423.9	3422667.5	937993.9	157129.9	21879.0

We expect the proportion of milk cows to be lower in rangelands (LG systems), where cattle are mainly held for beef production, and higher in the mixed smallholder (MR) systems. Our imputation method will generally enforce this expectation because 1) the ansatz whereby we impute the system-level data implies that the proportion of milk cows is a monotonically increasing function of the total cow population, 2) cattle density tends to be correlated with human population density (Robinson et al., 2014), and 3) rangeland systems, by their nature, occur in areas of relatively low human population density, and these areas thus contain relatively fewer cattle, as compared to MR system areas. See Appendix A.4 for a more mathematically detailed explanation.

3.5 Adoption rate and uptake period

Field experts in Tanzania, Rwanda, Uganda, and Ethiopia were contacted in order to assess local conditions influencing technology adoption. Their responses, summarized in Tables 7-9, convey moderate optimism about technology uptake, but also acknowledge considerable impediments in terms of access to financing, access to quality inputs and extension services, and infrastructure, which may hamper diffusion and uptake of the new technology. We were unable to contact field experts in Kenya and Burundi.

Table 7: Field expert opinion on adoption rate, diffusion time, and access to financing
(Note: For adoption rate and diffusion time, respondents were asked to give an actual adoption rate in %, and a diffusion time in years, but instead gave 1-5 scale ratings.)

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
Likely adoption rate (1=low, 5=high)	NR	3	2*	2**	4	NR
Diffusion time (1=short, 5=long)	NR	2	5	3	3	NR
Effectiveness of diffusion (1=not likely to spread at all, 5=likely to spread rapidly)	NR	2	2	4	3	NR
Access to financing (1= none, 5= easily accessible)	NR	2	4	3	5	NR

*Respondent gave a verbal response—"modest"—which we have interpreted numerically as 2.
**Respondent gave an actual adoption rate—25%—which we have assigned a scale rating of 2.

Table 8: Field expert opinion on the likelihood of new technology adoption in each production system (Scale of 1 to 5, where 1 = not at all likely and 5 = very likely)

	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	NR	2	1	2	NA	NR
LGH	NR	4	1	3	NA	NR
LGT	NR	5	1	3	NA	NR
MRA	NR	4	2	5	NA	NR
MRH	NR	5	4	4	3	NR
MRT	NR	5	3	4	4	NR

Table 9: Field expert opinion on most significant current constraints on production

Kenya	No response received
Tanzania	• Lack of national dairy herd • Shortage of year round availability of quality feeds • Inadequate dairy technology and agribusiness skill
Ethiopia	• Poor economic capacity (capital, land, labor) to absorb package of livestock & feed technologies (e.g., dairy breed plus improved forage).
Uganda	• Over reliance on natural weather conditions and seasons for production • Climate change and climate variability leading to feed shortage • Poor productivity and performance of indigenous breeds • Livestock pests and diseases • High cost on inputs and investments in livestock enterprise • Poor quality inputs • Competition on feedstuff resources between humans and livestock • Some of the policies especially on livestock health and breeding are not enforced • Poor national funding and investment in livestock research and related activities • Poor persistence of forage legumes in grass/legume mixture. • Emergence of new forage diseases and pests • Inadequate research funds, infrastructure and investment to generate appropriate knowledge to address farmers' tactical and strategic challenges. • Lack knowledge on suitable forage cultivars, agronomic management practices, conservation and utilization. • Farmers' inaccessibility to appropriate forage technologies and technical information.
Rwanda	• Physiological constraints: mammites problem • Biotic: Napier stunt and smut disease • Abiotic: drought and nutrient deficiency in the soil and aluminum soil toxicity • Environmental constraints: inadequate feeds quantities and qualities all year round
Burundi	No response received

Given this complex mix of promise and challenge, and given the significant gaps in the responses we received, we have decided to forgo the traditional point estimate format typically seen in economic surplus studies, and instead present results in an NPV heatmap and isoquant map format. These alternative formats allow the reader to examine outcomes for the adoption rate scenario(s) they deem reasonable or otherwise consistent with the local policy environment. They also allow one to quickly develop an intuition about how NPV outcomes vary with the assumed adoption rate.

Adoption over time is modeled using a logistic curve as seen in Figure 5. This two parameter curve reflects the typical slow start of adoption, followed by a period of rapid diffusion, and then a tapering off of uptake as the adoption rate ceiling is reached. The slope of the curve (i.e., the quickness with which adoption occurs) depends mathematically upon the duration of the uptake period (see Equation 6 in Appendix A.1 for further mathematical details). In Table 7, most respondents indicated a moderate or long uptake period, where the terms "moderate" and "long" are subject to a great deal of interpretation. Our interpretation for this study is that the uptake period (T_u) would last 20 years in all countries. As mentioned in section 3.1, the research period is expected to last 10 years. The total time horizon is thus 30 years from initiation of research to peak adoption.

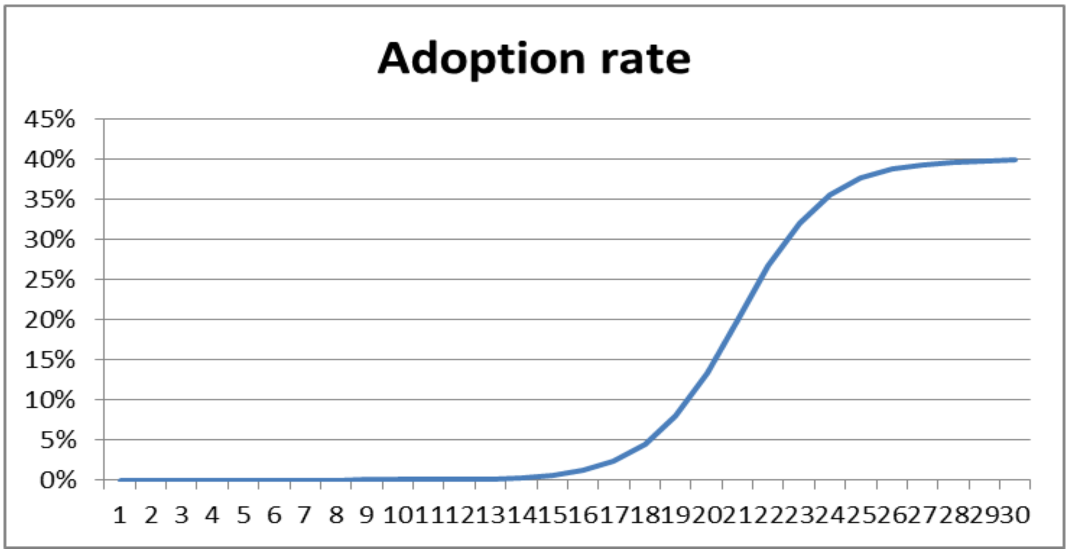


Figure 5: The logistic adoption curve

3.6 Supply/demand elasticities, depreciation, probability of success

As usual in economic surplus studies, estimates of the supply and demand elasticities for the precise commodity and geographical area in question are difficult to come by. We set the milk supply and demand elasticities, ε and η, to 0.7 and 0.5, respectively, in accordance with a forages study conducted in West Africa (Thornton & Tarawali, 1999, p. 100). The discount rate (r) is set to 10%. The breeding expert consulted for this study suggested that an improved forage technology could remain viable for 30 years or more from release (M. Peters, email correspondence, May 3, 2016). Discounting at 10% renders such depreciation negligible, and so we have held the depreciation parameter (δ_t) constant at 1 (no depreciation). Based on the success of past forage research programs for release in other parts of the world, we feel justified in setting the probability of success (p) at 80%.

The model parameters discussed in the subsections above are summarized in Table 10.

Table 10: Economic surplus model parameters

Parameter	Description	Value
$\boldsymbol{\varepsilon}$	Elasticity of milk supply	0.7
$\boldsymbol{\eta}$	Elasticity of milk demand	0.5
$\boldsymbol{p}$	Probability of success	80%
$\boldsymbol{\delta_t}$	Depreciation factor	1
$\boldsymbol{E[y]}$	Increase in productivity	15%-40%
$\boldsymbol{E[C]}$	Increase in variable cost	0%
$\boldsymbol{r}$	Discount rate	10%
$\boldsymbol{T_r}$	Length of research period	10 years
$\boldsymbol{T_u}$	Length of diffusion period	20 years

4. Results

In economic surplus studies such as this one, the NPV of a given research program can be sensitive to the choice of adoption rate, this choice often being an approximation based on expert opinion. Because estimates of adoption rates may be subjective and necessarily encapsulate a certain amount of uncertainty, they are often subject to a great deal of debate. In this study, the assessment of any single "probable" scenario is made more uncertain by the wide range of expected potential impacts the new technology might have on milk productivity (15%-40%). For these reasons, we decided to move beyond the typical point estimate format, which is capable of covering just a few scenario outcomes, in favor of a range of scenarios represented by a heatmap and isoquant format, which offers a broad overview of the outcomes landscape.

4.1 NPV outcomes heatmap

NPV outcomes are displayed in a heatmap format in Figures 6-8. The three heatmaps are calculated on a producer surplus, consumer surplus, and total surplus basis, respectively. The heatmaps cover a total of 240 scenarios involving different combinations of adoption rates and % increases in productivity. Each heatmap cell is colored in accordance with the NPV value it contains. Lower values are redder, higher values are greener; and the 50th percentile of NPV values is colored yellow. We also generated producer and total surplus heatmaps for each country and include these in Appendix A.5. When reviewing the country-level heatmaps, it must be kept in mind that NPV outcomes include diffusion costs, but not research costs.

	Program level (all countries, includes research cost)											
	NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
		Increase in productivity										
Adoption rate	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**	**55%**	**60%**
5%	-7,836	-4,500	-1,162	2,178	5,520	8,864	12,211	15,559	18,910	22,263	25,618	28,975
10%	-4,500	2,178	8,864	15,559	22,263	28,975	35,696	42,425	49,163	55,910	62,665	69,428
15%	-1,162	8,864	18,910	28,975	39,059	49,163	59,286	69,428	79,590	89,771	99,972	110,191
20%	2,178	15,559	28,975	42,425	55,910	69,428	82,982	96,569	110,191	123,848	137,538	151,264
25%	5,520	22,263	39,059	55,910	72,813	89,771	106,783	123,848	140,966	158,139	175,365	192,645
30%	8,864	28,975	49,163	69,428	89,771	110,191	130,689	151,264	171,916	192,645	213,452	234,336
35%	12,211	35,696	59,286	82,982	106,783	130,689	154,700	178,817	203,039	227,366	251,799	276,337
40%	15,559	42,425	69,428	96,569	123,848	151,264	178,817	206,508	234,336	262,302	290,405	318,646
45%	18,910	49,163	79,590	110,191	140,966	171,916	203,039	234,336	265,807	297,453	329,272	361,265
50%	22,263	55,910	89,771	123,848	158,139	192,645	227,366	262,302	297,453	332,818	368,399	404,194
55%	25,618	62,665	99,972	137,538	175,365	213,452	251,799	290,405	329,272	368,399	407,785	447,432
60%	28,975	69,428	110,191	151,264	192,645	234,336	276,337	318,646	361,265	404,194	447,432	490,979
65%	32,334	76,201	120,430	165,023	209,979	255,298	300,980	347,025	393,433	440,204	487,339	534,836
70%	35,696	82,982	130,689	178,817	227,366	276,337	325,728	375,541	425,774	476,429	527,505	579,002
75%	39,059	89,771	140,966	192,645	244,807	297,453	350,582	404,194	458,290	512,869	567,932	623,478
80%	42,425	96,569	151,264	206,508	262,302	318,646	375,541	432,985	490,979	549,524	608,618	668,262
85%	45,793	103,376	161,580	220,405	279,851	339,917	400,605	461,913	523,843	586,393	649,564	713,357
90%	49,163	110,191	171,916	234,336	297,453	361,265	425,774	490,979	556,880	623,478	690,771	758,760
95%	52,535	117,015	182,271	248,302	315,109	382,691	451,049	520,183	590,092	660,777	732,237	804,473
100%	55,910	123,848	192,645	262,302	332,818	404,194	476,429	549,524	623,478	698,291	773,963	850,496

Figure 6: Program level NPV outcomes heatmap on a producer surplus basis

	Program level (all countries, includes research cost)											
	NPV Scenario Heatmap (USD $,000), Consumer Surplus basis											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	-6,502	-1,832	2,841	7,517	12,196	16,878	21,563	26,251	30,942	35,636	40,333	45,033
10%	-1,832	7,517	16,878	26,251	35,636	45,033	54,442	63,863	73,296	82,741	92,198	101,667
15%	2,841	16,878	30,942	45,033	59,151	73,296	87,468	101,667	115,894	130,147	144,428	158,735
20%	7,517	26,251	45,033	63,863	82,741	101,667	120,642	139,665	158,735	177,854	197,021	216,237
25%	12,196	35,636	59,151	82,741	106,407	130,147	153,963	177,854	201,821	225,862	249,979	274,171
30%	16,878	45,033	73,296	101,667	130,147	158,735	187,432	216,237	245,150	274,171	303,300	332,538
35%	21,563	54,442	87,468	120,642	153,963	187,432	221,048	254,811	288,722	322,780	356,986	391,339
40%	26,251	63,863	101,667	139,665	177,854	216,237	254,811	293,579	332,538	371,691	411,035	450,573
45%	30,942	73,296	115,894	158,735	201,821	245,150	288,722	332,538	376,598	420,902	465,449	510,239
50%	35,636	82,741	130,147	177,854	225,862	274,171	322,780	371,691	420,902	470,413	520,226	570,339
55%	40,333	92,198	144,428	197,021	249,979	303,300	356,986	411,035	465,449	520,226	575,367	630,872
60%	45,033	101,667	158,735	216,237	274,171	332,538	391,339	450,573	510,239	570,339	630,872	691,839
65%	49,736	111,149	173,070	235,500	298,438	361,884	425,839	490,302	555,274	620,753	686,742	753,238
70%	54,442	120,642	187,432	254,811	322,780	391,339	460,487	530,225	600,552	671,468	742,975	815,071
75%	59,151	130,147	201,821	274,171	347,198	420,902	495,282	570,339	646,073	722,484	799,572	877,336
80%	63,863	139,665	216,237	293,579	371,691	450,573	530,225	610,647	691,839	773,801	856,533	940,035
85%	68,578	149,194	230,680	313,034	396,258	480,352	565,314	651,146	737,848	825,418	913,858	1,003,167
90%	73,296	158,735	245,150	332,538	420,902	510,239	600,552	691,839	784,100	877,336	971,547	1,066,732
95%	78,017	168,289	259,647	352,090	445,620	540,235	635,936	732,723	830,596	929,555	1,029,600	1,130,730
100%	82,741	177,854	274,171	371,691	470,413	570,339	671,468	773,801	877,336	982,075	1,088,017	1,195,161

Figure 7: Program level NPV outcomes heatmap on a consumer surplus basis

Program level (all countries, includes research cost)

NPV Scenario Heatmap (USD $,000), Total Surplus basis

Adoption rate		Increase in productivity											
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	-3,169	4,837	12,848	20,864	28,885	36,911	44,942	52,979	61,021	69,067	77,119	85,177
	10%	4,837	20,864	36,911	52,979	69,067	85,177	101,306	117,457	133,628	149,820	166,032	182,265
	15%	12,848	36,911	61,021	85,177	109,379	133,628	157,923	182,265	206,653	231,088	255,569	280,096
	20%	20,864	52,979	85,177	117,457	149,820	182,265	214,793	247,403	280,096	312,871	345,729	378,669
	25%	28,885	69,067	109,379	149,820	190,389	231,088	271,915	312,871	353,956	395,170	436,513	477,985
	30%	36,911	85,177	133,628	182,265	231,088	280,096	329,290	378,669	428,234	477,985	527,922	578,044
	35%	44,942	101,306	157,923	214,793	271,915	329,290	386,917	444,797	502,930	561,316	619,954	678,845
	40%	52,979	117,457	182,265	247,403	312,871	378,669	444,797	511,255	578,044	645,162	712,610	780,388
	45%	61,021	133,628	206,653	280,096	353,956	428,234	502,930	578,044	653,575	729,523	805,890	882,674
	50%	69,067	149,820	231,088	312,871	395,170	477,985	561,316	645,162	729,523	814,401	899,794	985,702
	55%	77,119	166,032	255,569	345,729	436,513	527,922	619,954	712,610	805,890	899,794	994,322	1,089,474
	60%	85,177	182,265	280,096	378,669	477,985	578,044	678,845	780,388	882,674	985,702	1,089,474	1,193,987
	65%	93,239	198,519	304,670	411,692	519,586	628,351	737,988	848,496	959,876	1,072,127	1,185,249	1,299,243
	70%	101,306	214,793	329,290	444,797	561,316	678,845	797,384	916,934	1,037,495	1,159,067	1,281,649	1,405,242
	75%	109,379	231,088	353,956	477,985	603,174	729,523	857,033	985,702	1,115,532	1,246,522	1,378,672	1,511,983
	80%	117,457	247,403	378,669	511,255	645,162	780,388	916,934	1,054,801	1,193,987	1,334,493	1,476,320	1,619,466
	85%	125,540	263,739	403,429	544,608	687,278	831,438	977,088	1,124,229	1,272,859	1,422,980	1,574,591	1,727,693
	90%	133,628	280,096	428,234	578,044	729,523	882,674	1,037,495	1,193,987	1,352,150	1,511,983	1,673,487	1,836,661
	95%	141,721	296,473	453,087	611,561	771,898	934,095	1,098,155	1,264,075	1,431,857	1,601,501	1,773,006	1,946,373
	100%	149,820	312,871	477,985	645,162	814,401	985,702	1,159,067	1,334,493	1,511,983	1,691,535	1,873,149	2,056,826

Figure 8: Program level NPV outcomes heatmap on a total surplus basis

4.2 NPV outcomes isoquant map

We used the Excel Solver Add-in to generate the isoquant map in Figure 9. Analogous to elevation maps, each isoquant on the map represents an NPV outcome "contour." That is to say, each isoquant curve represents the locus of possible combinations of productivity increase and adoption rate that will result in a particular NPV outcome. Any such combination along a given isoquant will result in the same NPV outcome. The internal rate of return (IRR) associated with each NPV isoquant is displayed in the map legend.

When plotted in logs as in Figure 10, the isoquants become straight lines with a slope very close to -1. This implies that, regardless of NPV outcome, a one-to-one tradeoff exists between the adoption rate and the expected % increase in productivity. If the increase in productivity falls some percentage below expectations, the same level of NPV will still be achieved so long as the associated adoption rate is the same percentage *above* expectations.

4.3 The NPV scenario envelope

Based on the logged map, we can go one step further and deduce a simple formula for determining the adoption rate necessary to achieve any given NPV outcome for a given % increase in productivity. In Figure 10, a trendline is fitted to the topmost logged isoquant, and its equation is displayed on the graph. Trendline equations for all of the logged isoquants are displayed in Table 11.

A plot of the y-intercept terms in Table 11 against the log of their associated NPV values reveals an interesting relation (Figure 11). Based on this relation, the y-intercepts in Table 11 can be approximately expressed in terms of their corresponding NPV and the two fitted parameters displayed in Figure 11. Since the slopes of all isoquants are all nearly equal to -1, we can establish the following general NPV isoquant formula:

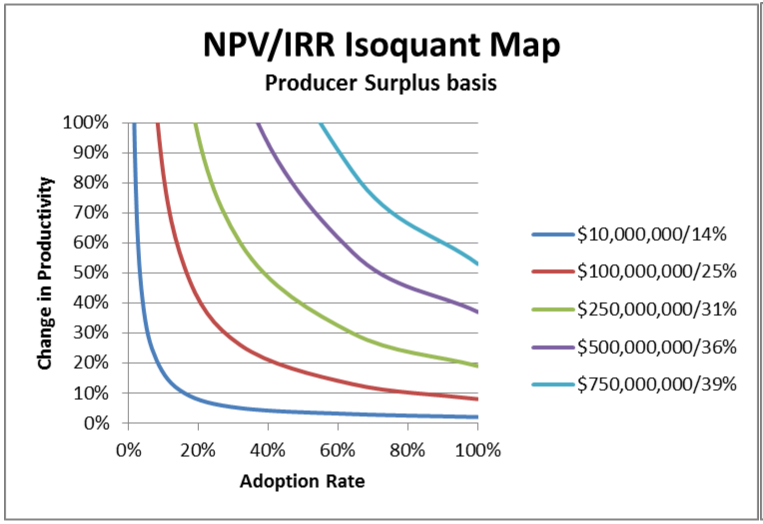
$$\ln A_{max} \approx -\ln E[y] + 0.8056 \ln NPV + 7.9655 \qquad \textbf{Eq. 1}$$

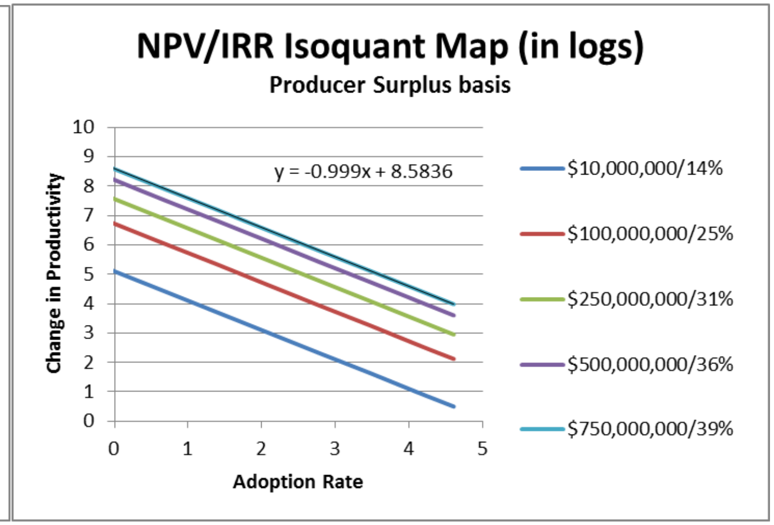
Which can be simplified to:

$$A_{max} \approx \frac{NPV^{0.8056}}{E[y]} e^{7.9655} \qquad \textbf{Eq. 2}$$

This is an envelope equation in which the adoption rate ceiling (A_{max}), the expected percentage increase in productivity ($E[y]$), and NPV are allowed to vary, with all other model parameters held constant at the values displayed in Tables 6 and 10. The parameter values in Tables 6 and 10 are encoded in the two fitted parameters 0.8056 and 7.9655. This equation allows us to explicitly determine the adoption rate ceiling required in order to achieve a specific NPV outcome of interest, given a certain % increase in productivity (or vice versa). Before deducing this formula, such calculations must be made using a root finding algorithm.

Envelope equations can also be generated on a total surplus or consumer surplus basis following the same steps described above.





Figures 9 and 10: Scenario isoquant maps

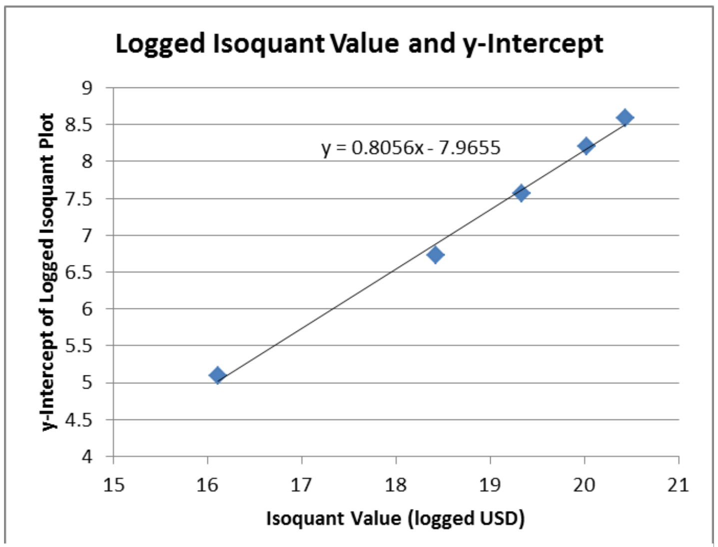


Figure 11: A plot of the log of the Isoquant NPV values in Table 11 against their corresponding y-intercept values

Table 11: Logged isoquant trendline equations

NPV Isoquant (USD)	Fitted trendline equation
10,000,000	$\ln A_{max} = -0.9986 \ln E[y] + 5.0993$
100,000,000	$\ln A_{max} = -0.9998 \ln E[y] + 6.7240$
250,000,000	$\ln A_{max} = -1.0000 \ln E[y] + 7.5600$
500,000,000	$\ln A_{max} = -0.9998 \ln E[y] + 8.2073$
750,000,000	$\ln A_{max} = -0.9990 \ln E[y] + 8.5836$

4.4 Sensitivity analysis

NPV outcome sensitivity to inaccuracy in five of the model parameters was calculated on a total surplus basis. Sensitivity to each parameter is again presented in a heatmap format, with each cell indicating the sensitivity of the corresponding NPV outcome in Figure 8. Sensitivity is expressed as the percentage change in NPV given a 1% change in the given parameter (see Appendix A.2 for mathematical details). Sensitivity with an absolute value close to 1%, for example, means that the NPV outcome will be roughly as inaccurate as the parameter value itself. In these maps, green indicates relatively lower sensitivity, while red indicates relatively higher sensitivity, and yellow indicates the 50th percentile of values.

Sensitivity to supply and demand elasticities

The economic surplus model employed in this study makes use of supply and demand elasticities which are generally too expensive and time consuming to estimate directly, and which must therefore be compiled from among secondary sources. In this study, the milk supply and demand elasticities (ε and η) were taken from a West Africa forages study. As the geographical characteristics are quite different between West and East Africa, this source invites analysis of model sensitivity to variation in these two parameters.

We found considerable model sensitivity to changes in supply elasticity, ranging from -1.07% to -1% across most scenarios, and becoming precipitously more sensitive towards the upper left corner of the heatmap (Figure 12). Sensitivity to changes in the demand elasticity, on the other hand, is negligible, ranging between 0% and 0.4% (Figure 13).

Sensitivity to the % change in variable cost

Considerable uncertainty also surrounds the value of the expected % increase in variable cost ($E[C]$) associated with the new technology. As discussed in section 2, the improved forages require less fertilizer, thus reducing input costs. However, this might not necessarily translate into reduced cost for cut-and-carry farmers. And many smallholders growing their own forage might introduce the improved cultivars in a complementary role, potentially displacing a cash crop and thereby incurring a cost in the form of forgone revenue.

We found that model sensitivity to inaccuracy in the % increase in variable cost is not as pronounced as it is to the supply elasticity, but is still considerable, ranging between -1% and -0.67% across most scenarios, and becoming precipitously more sensitive towards the upper left corner of the heatmap (Figure 14).

Sensitivity to the % increase in productivity, producer price, and quantity affected

A degree of uncertainty also surrounds the expected % increase in productivity ($E[y]$), producer price (P), and quantity affected (Q). Sensitivity to $E[y]$ is considerable, ranging from 1% to 1.07% (Figure 15). Sensitivity to P and Q is also considerable, ranging from 1% to 1.04% across most scenarios, and becoming precipitously more sensitive towards the upper left corner of the heatmap (Figure 16).

		NPV (TS) Sensitivity w.r.t. supply elasticity (e)											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
Adoption rate	5%	-1.61	-1.22	-1.13	-1.10	-1.08	-1.06	-1.05	-1.05	-1.04	-1.04	-1.04	-1.03
	10%	-1.22	-1.10	-1.06	-1.05	-1.04	-1.03	-1.03	-1.03	-1.02	-1.02	-1.02	-1.02
	15%	-1.13	-1.06	-1.04	-1.03	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	20%	-1.10	-1.05	-1.03	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	25%	-1.08	-1.04	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	30%	-1.06	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	35%	-1.05	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	40%	-1.05	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	45%	-1.04	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02
	50%	-1.04	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03
	55%	-1.04	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03
	60%	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03
	65%	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03
	70%	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.03
	75%	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.03	-1.03
	80%	-1.03	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.03	-1.04
	85%	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.04	-1.04
	90%	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04
	95%	-1.02	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04
	100%	-1.02	-1.02	-1.02	-1.02	-1.02	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04

Figure 12: NPV (total surplus basis) sensitivity heatmap with respect to inaccuracy in the supply elasticity parameter

		NPV (TS) Sensitivity w.r.t. demand elasticity (n)											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
Adoption rate	5%	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
	10%	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.01
	15%	.0	.0	.0	.0	.0	.0	.0	.01	.01	.01	.01	.01
	20%	.0	.0	.0	.0	.0	.01	.01	.01	.01	.01	.01	.01
	25%	.0	.0	.0	.0	.01	.01	.01	.01	.01	.01	.01	.01
	30%	.0	.0	.0	.01	.01	.01	.01	.01	.01	.01	.01	.01
	35%	.0	.0	.0	.01	.01	.01	.01	.01	.01	.01	.01	.02
	40%	.0	.0	.01	.01	.01	.01	.01	.01	.01	.02	.02	.02
	45%	.0	.0	.01	.01	.01	.01	.01	.01	.02	.02	.02	.02
	50%	.0	.0	.01	.01	.01	.01	.01	.02	.02	.02	.02	.02
	55%	.0	.0	.01	.01	.01	.01	.01	.02	.02	.02	.02	.02
	60%	.0	.01	.01	.01	.01	.01	.02	.02	.02	.02	.02	.03
	65%	.0	.01	.01	.01	.01	.01	.02	.02	.02	.02	.03	.03
	70%	.0	.01	.01	.01	.01	.02	.02	.02	.02	.03	.03	.03
	75%	.0	.01	.01	.01	.01	.02	.02	.02	.02	.03	.03	.03
	80%	.0	.01	.01	.01	.02	.02	.02	.02	.03	.03	.03	.03
	85%	.0	.01	.01	.01	.02	.02	.02	.03	.03	.03	.03	.04
	90%	.0	.01	.01	.01	.02	.02	.02	.03	.03	.03	.04	.04
	95%	.0	.01	.01	.01	.02	.02	.02	.03	.03	.03	.04	.04
	100%	.0	.01	.01	.02	.02	.02	.03	.03	.03	.04	.04	.04

Figure 13: NPV (total surplus basis) sensitivity heatmap with respect to inaccuracy in the demand elasticity parameter

		NPV (TS) Sensitivity w.r.t. expected change in input cost (Ec)											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
Adoption rate	5%	-1.53	-1.11	-.99	-.91	-.86	-.82	-.78	-.75	-.72	-.69	-.67	-.65
	10%	-1.16	-1.0	-.93	-.87	-.83	-.80	-.76	-.73	-.71	-.68	-.66	-.64
	15%	-1.08	-.97	-.91	-.86	-.82	-.79	-.76	-.73	-.71	-.68	-.66	-.64
	20%	-1.05	-.95	-.90	-.86	-.82	-.79	-.76	-.73	-.70	-.68	-.66	-.64
	25%	-1.03	-.95	-.89	-.85	-.82	-.79	-.76	-.73	-.71	-.68	-.66	-.64
	30%	-1.01	-.94	-.89	-.85	-.82	-.79	-.76	-.73	-.71	-.68	-.66	-.64
	35%	-1.0	-.94	-.89	-.85	-.82	-.79	-.76	-.73	-.71	-.69	-.66	-.64
	40%	-1.0	-.93	-.89	-.85	-.82	-.79	-.76	-.73	-.71	-.69	-.67	-.65
	45%	-.99	-.93	-.89	-.85	-.82	-.79	-.76	-.73	-.71	-.69	-.67	-.65
	50%	-.99	-.93	-.89	-.85	-.82	-.79	-.76	-.74	-.71	-.69	-.67	-.65
	55%	-.99	-.93	-.89	-.85	-.82	-.79	-.76	-.74	-.71	-.69	-.67	-.65
	60%	-.98	-.93	-.89	-.85	-.82	-.79	-.76	-.74	-.72	-.69	-.67	-.65
	65%	-.98	-.93	-.89	-.85	-.82	-.79	-.77	-.74	-.72	-.70	-.68	-.66
	70%	-.98	-.93	-.89	-.85	-.82	-.79	-.77	-.74	-.72	-.70	-.68	-.66
	75%	-.98	-.93	-.89	-.85	-.82	-.79	-.77	-.74	-.72	-.70	-.68	-.66
	80%	-.98	-.93	-.89	-.86	-.82	-.80	-.77	-.75	-.72	-.70	-.68	-.66
	85%	-.98	-.93	-.89	-.86	-.83	-.80	-.77	-.75	-.72	-.70	-.68	-.67
	90%	-.98	-.93	-.89	-.86	-.83	-.80	-.77	-.75	-.73	-.71	-.69	-.67
	95%	-.98	-.93	-.89	-.86	-.83	-.80	-.77	-.75	-.73	-.71	-.69	-.67
	100%	-.98	-.93	-.89	-.86	-.83	-.80	-.78	-.75	-.73	-.71	-.69	-.67

Figure 14: NPV (total surplus basis) sensitivity heatmap with respect to inaccuracy in the % change in variable cost

	NPV (TS) Sensitivity w.r.t. expected change in productivity (Ey)											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10%	1.0	1.0	1.0	1.0	1.0	1.0	1.01	1.01	1.01	1.01	1.01	1.01
15%	1.0	1.0	1.0	1.0	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
20%	1.0	1.0	1.0	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.02
25%	1.0	1.0	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02
30%	1.0	1.0	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.02	1.02
35%	1.0	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.02	1.02	1.03
40%	1.0	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.02	1.03	1.03	1.03
45%	1.0	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	1.03
50%	1.0	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	1.03	1.04
55%	1.0	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	1.04	1.04
60%	1.0	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	1.04	1.04	1.04
65%	1.0	1.01	1.01	1.02	1.02	1.03	1.03	1.03	1.04	1.04	1.04	1.05
70%	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.04	1.05	1.05
75%	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.05	1.06
80%	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.04	1.05	1.05	1.06
85%	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.05	1.06	1.06
90%	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.06	1.06	1.07
95%	1.01	1.01	1.02	1.02	1.03	1.04	1.04	1.05	1.05	1.06	1.06	1.07
100%	1.01	1.01	1.02	1.03	1.03	1.04	1.04	1.05	1.06	1.06	1.07	1.07

Figure 15: NPV (total surplus basis) sensitivity heatmap with respect to inaccuracy in the % change in productivity

	NPV (TS) Sensitivity w.r.t. producer price or quantity affected (P or Q)											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	1.61	1.22	1.13	1.10	1.08	1.06	1.05	1.05	1.04	1.04	1.03	1.03
10%	1.22	1.10	1.06	1.05	1.04	1.03	1.03	1.02	1.02	1.02	1.02	1.01
15%	1.13	1.06	1.04	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01
20%	1.10	1.05	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01
25%	1.08	1.04	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
30%	1.06	1.03	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
35%	1.05	1.03	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.0	1.0
40%	1.05	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.0	1.0	1.0
45%	1.04	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0
50%	1.04	1.02	1.01	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0
55%	1.03	1.02	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0
60%	1.03	1.01	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0
65%	1.03	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0
70%	1.03	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0
75%	1.02	1.01	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0
80%	1.02	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
85%	1.02	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
90%	1.02	1.01	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
95%	1.02	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
100%	1.02	1.01	1.01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Figure 16: NPV (total surplus basis) sensitivity heatmap with respect to inaccuracy in producer price or quantity affected

5. Discussion

At the program level, the results of the economic surplus analysis, based on the available data and given the underlying assumptions, generally suggest that investment in a research program for the development of improved forage varieties for release in East Africa would be a low risk, high reward endeavor. Preliminary data from ongoing multi-site trials in Kenya and Rwanda suggests that release and uptake of improved forages would raise milk productivity by 15%-40%. On a producer surplus basis, NPV outcomes in this range are in the tens of millions of dollars so long as the adoption rate is greater than 10%, and rise quickly for a wide range of plausible adoption rates. A modest adoption rate ceiling of 30%, for example, requires only a 30% increase in productivity—well within the expected range of 15%-40% reported by experts—in order to result in producer-side NPV outcomes greater than $100 million. If we include consumer-side benefits, the NPV outcomes are much greater, reaching half a billion dollars for a wide range of plausible scenarios.

At the country level, projected NPV outcomes are essentially a reflection of milk cow population sizes—highest in Ethiopia, followed by Tanzania, Kenya, Uganda, Rwanda, and Burundi. However, when analyzed in terms of NPV per milk cow, the best results are found in the countries with the smallest cow populations, Rwanda and Burundi, followed by Kenya, Ethiopia, Uganda, and Tanzania. With the country level results, it is important to keep in mind that NPV outcomes at this level do not include program level research cost.

As far as the inner workings of the model are concerned, the overwhelmingly positive assessment is due in large part to the massive pool of potential beneficiaries in the study area (reflected in Q), and because we assume there is no increase in input costs associated with adoption of the new technology ($E[C] = 0$). The relatively brief research period (T_r), compared to prior CIAT forage research programs, also contributes to this result.

Sensitivity analysis reveals that the accuracy of our NPV outcomes is robust to uncertainty in milk demand elasticity, but vulnerable to the same in the milk supply elasticity parameter, the expected % change in variable cost, the expected % increase in productivity, the producer price, and the quantity affected. For most of the scenarios covered in the heatmaps, our NPV outcomes will be as inaccurate as our estimate of any one of these key parameters. However, we can infer that, taking account only of producer-side net benefits (Figure 6), NPV outcomes in the expected range of percentage productivity increases, and an adoption rate of at least 10%, would not turn negative even with an inaccuracy as high as 50% in any single one of the parameters examined in section 4.4. For a wide range of plausible scenarios such inaccuracy would merely mean the difference between an 8^{th} order result ($100s of millions) and a 7^{th} order result ($10s of millions). Major inaccuracies would have to occur in several parameters simultaneously in order to critically skew the model output.

When interpreting these results, it should be kept in mind that the economic surplus model employed in this study is a parsimonious, minimum data approach. This approach thus simplifies many important features of the underlying reality. In particular, we ignore any transition costs that might be associated with adoption of the new technology. More significantly, the model does not account for farm heterogeneity. That is to say, the model assumes that the percentage increase in productivity is the same for all adopting farms, regardless of variation in local conditions. Because of data limitations, our estimate of the production affected by the new technology is based on the national average yield, effectively introducing the assumption that yields are the same across all farms, regardless of variation in local conditions. These simplifications in representation may bias our NPV outcomes upward, depending on the structure of the heterogeneity present in the region. We also assume that the supply and demand elasticities, adoption rate ceilings, and uptake period durations are the same across all countries and across all production systems, although it is not clear in which direction these assumptions might drive the results.

On the other hand, our results are conservative in some respects. For example, we have taken no account of the additional benefits that might arise from increased meat production, enhanced production via leguminous intercropping, the storage and/or sale of hay, and the spread of climate adapted push-pull systems.

6. Conclusion

The results of our assessment suggest that investment in a research program for the development of improved forage varieties for release in East Africa would be a low risk, high reward endeavor. The economic surplus model output indicates that, even if adoption rate ceilings and expected % increases in productivity fall below current expectations, such a research program would likely generate discounted benefits on the order of many tens of millions of dollars.

Our results are subject to the effects of uncertainty in several key parameters, but the NPV outcomes are adequately large that inaccuracy in any single parameter is unlikely to reduce these values by a significant amount. For a wide range of plausible scenarios, a major inaccuracy in one of these parameters could potentially reduce the NPV up to an order of magnitude, but still with substantial positive effects.

In short, investment in improved forages has high potential return for dairy producers in East Africa. Key areas of investigation that could improve this model include better understanding of supply and demand elasticities, better characterization of the regional heterogeneity, and improved consideration of costs association with the diffusion of the technology. Nevertheless, there is great potential for forage technology in East Africa if wide scale adoption can be achieved.

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Appendix

A.1 The economic surplus model

In this study, benefits are defined in terms of the change in producer, consumer, or total surplus resulting from adoption of the new technology. We use Alston et al.'s economic surplus model to calculate these benefits (1995). The commodity in question is a perishable good which is not traded internationally; and so we use the closed economy equations. These are defined by Alston et al. as follows (1995, pp. 360, 380–5).

The annual change in total surplus:

$$\Delta TS_t = K_t PQ\left(1 + \frac{1}{2}Z_t\eta\right) \quad \text{Eq. 3}$$

Where Z_t is the proportionate decrease in price in year t, defined as:

$$Z_t = \frac{K_t\varepsilon}{\varepsilon + \eta} \quad \text{Eq. 4}$$

And K_t is the supply curve shift in year t:

$$K_t = \left[\frac{E[Y]}{\varepsilon} - \frac{E[C]}{1 + E[Y]}\right] pA_t\delta_t \quad \text{Eq. 5}$$

Where A_t is the adoption rate in any given year of uptake, and is determined by a logistic curve:

$$A_t = \frac{A_{max}}{1 + e^{-(\alpha+\beta t)}} \quad \text{Eq. 6}$$

Where A_{max} is the adoption rate ceiling, and the parameters α and β control displacement and slope, respectively; and are determined by the duration of research and the duration of uptake.

The annual change in consumer surplus is defined as:

$$\Delta CS_t = Z_t PQ\left(1 + \frac{1}{2}Z_t\eta\right) \quad \text{Eq. 7}$$

The annual change in producer surplus is defined as:

$$\Delta PS_t = \Delta TS_t - \Delta CS_t \quad \text{Eq. 8}$$

The other parameters in equations 3-5 are defined in Table 10.

The net present value of the research program is then calculated as:

$$NPV = \sum\nolimits_t^T \frac{\Delta TS_t - k_t}{(1 + r)^t} \quad \text{Eq. 9}$$

Where k_t is the program level cost in year t.

A.2 NPV derivatives w.r.t. key parameters

The derivatives of the NPV of the program benefit-cost stream with respect to key model parameters are displayed below. Benefits in each period are measured in terms of the change in total surplus (ΔTS_t).

These are the formulas used to perform sensitivity analysis in section 4.4. Sensitivity to any given parameter u is calculated as the percentage change in NPV given a percentage change in u:

$$\frac{\%\Delta NPV}{\%\Delta u} = \frac{\partial \ln NPV}{\partial \ln u} = \frac{\partial NPV}{\partial u}\frac{u}{NPV} \qquad \text{Eq. 10}$$

The derivatives of NPV w.r.t. to key model parameters follow.

W.r.t. the supply elasticity (ε):

$$\frac{\partial NPV}{\partial \varepsilon} = \sum_{t=1}^{T} \frac{1}{(1+r)^t}\left(\frac{\partial K_t}{\partial \varepsilon}\frac{\Delta TS_t}{K_t} + \frac{1}{2}K_t PQ\eta\frac{\partial Z_t}{\partial \varepsilon}\right) \qquad \text{Eq. 11}$$

Where

$$\frac{\partial Z_t}{\partial \varepsilon} = \frac{Z_t}{K_t}\left(\frac{\partial K_t}{\partial \varepsilon} + Z_t\frac{\eta}{\varepsilon^2}\right) \qquad \text{Eq. 12}$$

And

$$\frac{\partial K_t}{\partial \varepsilon} = -\frac{E[y]}{\varepsilon^2}pA_t\delta_t \qquad \text{Eq. 13}$$

W.r.t. the demand elasticity (η):

$$\frac{\partial NPV}{\partial \eta} = PQ\frac{1}{2}\sum_{t=1}^{T}\frac{K_t}{(1+r)^t}\left(\frac{\partial Z_t}{\partial \eta}\eta + Z_t\right) \qquad \text{Eq. 14}$$

Where

$$\frac{\partial Z_t}{\partial \eta} = -\frac{Z_t^2}{\varepsilon K_t} \qquad \text{Eq. 15}$$

W.r.t. the expected increase in cost ($E[C]$):

$$\frac{\partial NPV}{\partial E[C]} = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left(\frac{\partial K_t}{\partial E[C]} \frac{\Delta TS_t}{K_t} + \frac{1}{2} K_t PQ\eta \frac{\partial Z_t}{\partial E[C]} \right) \quad \textbf{Eq. 16}$$

Where

$$\frac{\partial Z_t}{\partial E[C]} = \frac{\partial K_t}{\partial E[C]} \frac{Z_t}{K_t} \quad \textbf{Eq. 17}$$

and

$$\frac{\partial K_t}{\partial E[C]} = -\frac{pA_t\delta_t}{1+E[y]} \quad \textbf{Eq. 18}$$

W.r.t. the expected increase in productivity ($E[y]$):

$$\frac{\partial NPV}{\partial E[y]} = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left(\frac{\partial K_t}{\partial E[C]} \frac{\Delta TS_t}{K_t} + \frac{1}{2} K_t PQ\eta \frac{\partial Z_t}{\partial E[y]} \right) \quad \textbf{Eq. 19}$$

Where

$$\frac{\partial Z_t}{\partial E[y]} = \frac{\partial K_t}{\partial E[y]} \frac{Z_t}{K_t} \quad \textbf{Eq. 20}$$

and

$$\frac{\partial K_t}{\partial E[y]} = \left(\frac{1}{\varepsilon} + \frac{E[C]}{(1+E[y])^2} \right) pA_t\delta_t \quad \textbf{Eq. 21}$$

W.r.t. the quantity affected (Q) and price (P):

$$\frac{\partial NPV}{\partial Q} = \frac{1}{Q} \sum_{t=1}^{T} \frac{\Delta TS_t}{(1+r)^t} = \frac{PV}{Q} \quad \textbf{Eq. 22}$$

$$\frac{\partial NPV}{\partial P} = \frac{1}{P} \sum_{t=1}^{T} \frac{\Delta TS_t}{(1+r)^t} = \frac{PV}{P} \quad \textbf{Eq. 23}$$

In both these cases, then, the percentage change in *NPV* given a percentage change in the parameter is:

$$\frac{\partial \ln NPV}{\partial \ln(P\ or\ Q)} = \frac{PV}{NPV} \qquad \textbf{Eq. 24}$$

A.3 Diffusion cost

The diffusion cost (DC) is modeled as follows:

$$DC = \lambda \boldsymbol{M}^{\rho}\ ;\ \ \lambda = \$0.10, \qquad \rho = 0.97 \qquad \textbf{Eq. 25}$$

Where, for a given country, $\boldsymbol{M}$ is the number of milk producing cows, $\boldsymbol{\lambda}$ is the diffusion cost per cow, and $\boldsymbol{\rho}$ is the percentage increase in the diffusion cost per percentage increase in number of milk cows. Since we have set $\boldsymbol{\rho < 1}$, diffusion cost is marginally diminishing in milk cow population size.

A.4 Imputation of system-level milk cow population size

In order to impute milk cow population size at the production system level, we first summed the total cow population in each production system zone by overlaying the production system map in Figure 1 onto the cattle density map in Figure 2. These tallies are displayed in Table 12.

The empirical relation observed in Figures 3 and 4 can be expressed mathematically as follows:

$$\boldsymbol{M} = e^{-b}\boldsymbol{C}^{a} \qquad \textbf{Eq. 26}$$

Where $\boldsymbol{M}$ is the country-level milk cow population size reported by FAOSTAT, which can be estimated as a function of the total cow population $\boldsymbol{C}$; and a and b are parameters fitted to the data. In the 2010 graph (Figure 3), $a = 1.1113$ and $b = 3.2355$.

We hypothesized that this relation is scale invariant, and could be used as an ansatz to model milk cow population size at sub-national levels of disaggregation. That is, the number of milk cows in a given production system could be imputed using the ansatz:

$$M_i = e^{-b}C_i^{a} \qquad \textbf{Eq. 27}$$

Where the i indexes production system, and the values of a and b must be close to their values at the country level.

Table 12: 2010 total cattle disaggregated by production system						
	Burundi	**Ethiopia**	**Kenya**	**Rwanda**	**Tanzania**	**Uganda**
LGA	0	3322170	4116976	0	1223012	241273
LGH	0	121460	284307	0	564216	1086028
LGT	0	258146	702903	0	50289	102367
LGY	0	0	561	0	3669	0
MIA	0	245343	61238	0	75888	0
MIH	7350	4296	78049	5613	24176	5223
MIT	2733	803015	222326	7286	3972	1677
MRA	0	9432923	2125379	0	6013215	109421
MRH	47738	2118675	2365977	265964	6196315	6413741
MRT	291155	31407804	6303699	842509	1869350	1227967
MRY	0	0	706	0	15504	0
Other	185255	2008340	1022597	129776	1647486	2531685
Urban	8995	595027	394850	43232	841544	80244
Total	543226	50317198	17679567	1294381	18528635	11799625
FAOSTAT total (2010)	596412	53382192	17862852	1334820	19245648	12103532
% difference	-9.8%	-6.1%	-1.0%	-3.1%	-3.9%	-2.6%
MR Subtotal*	338892	42959402	10795761	1108473	14094384	7751129
MR tot as % of total	56.8%	80.5%	60.4%	83.0%	73.2%	64.0%
LG Subtotal**	0	3701775	5104186	0	1837517	1429668
LG tot as % of total	0.0%	7.4%	28.9%	0.0%	9.9%	12.1%

*Excluding MRY, **Excluding LGY

We do not have the disaggregated system level data necessary to test this hypothesis. (If we did, then there would be no need to invent this imputation method.) As a second-best approach, for each country in the study we fit the parameters a and b in Eq. 27 using the system level cow totals (C_i) that were summed in Table 13 and the FAOSTAT country-level total. That is, for each country, we fit a and b such that:

$$\sum_{i}^{n} e^{-b} C_i^a - \boldsymbol{M} = 0 \qquad \text{Eq. 28}$$

The fit was performed using the Excel Solver Add-in.

We then checked to see if the fitted values of a and b were close to their country-level values. In every case, they were close to within 10^{-1}. These system-level fitted values for a

and b are displayed in Table 13, along with the system-level milk cow totals imputed using Eq. 27.

Table 13: 2010 milk cow population disaggregated by production system (imputed)

	Burundi	Ethiopia	Kenya	Rwanda	Tanzania	Uganda
LGA	0	604426	1206593	0	387963	49973
LGH	0	15895	58696	0	160008	271778
LGT	0	36416	163398	0	10048	19036
LGY	0	0	51	0	502	0
MIA	0	34435	10338	0	16094	0
MIH	809	403	13602	681	4344	668
MIT	269	126832	44444	914	549	186
MRA	0	1904157	571189	0	2402413	20519
MRH	6509	368579	644850	53412	2486344	2006596
MRT	48807	7146898	1953577	196715	630577	312081
MRY	0	0	66	0	2612	0
Other	29492	347528	249688	23729	545660	704691
Urban	1014	91217	85105	6847	252884	14472
Imputed total	86900	10676785	5001599	282298	6899999	3400000
Faostat total (2010)	86900	10676783	5001600	282300	6900000	3400000
% difference	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MR Subtotal*	55316	9419634	3169616	250127	5519334	2339196
MR tot as % of total	63.7%	88.2%	63.4%	88.6%	80.0%	68.8%
LG Subtotal**	0	656736	1428688	0	558019	340787
LG tot as % of total	0.0%	6.2%	28.6%	0.0%	8.1%	10.0%
a	1.114	1.100	1.131	1.131	1.145	1.126
b	3.223	3.200	3.224	3.238	3.178	3.133

*Excluding MRY, **Excluding LGY

Note that the proportion of milk cows to total cows in a given production system is a monotonically increasing function of total cows in the system:

$$\frac{M_i}{C_i} = e^{-b} C_i^{a-1} \qquad \text{Eq. 29}$$

Since cattle density is correlated with human population density, and since LG systems occur in areas of low human population density relative to MR systems, then Eq. 29 implies that milk cow population as a proportion of the total cow population in LG systems will be strictly less than this proportion in MR systems, as expected.

A.5 Scenario heat maps by country

NPV heatmaps for each country are presented below on a producer surplus and total surplus basis. Keep in mind that these heatmaps include diffusion costs but not program research costs.

		Kenya (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
			Increase in productivity										
		5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**	**55%**	**60%**
	5%	312	1,090	1,869	2,648	3,428	4,208	4,989	5,771	6,553	7,335	8,118	8,901
Adoption rate	**10%**	1,090	2,648	4,208	5,771	7,335	8,901	10,469	12,040	13,612	15,186	16,762	18,341
	15%	1,869	4,208	6,553	8,901	11,254	13,612	15,974	18,341	20,712	23,088	25,468	27,853
	20%	2,648	5,771	8,901	12,040	15,186	18,341	21,503	24,674	27,853	31,039	34,234	37,437
	25%	3,428	7,335	11,254	15,186	19,131	23,088	27,057	31,039	35,034	39,041	43,061	47,093
	30%	4,208	8,901	13,612	18,341	23,088	27,853	32,636	37,437	42,256	47,093	51,948	56,821
	35%	4,989	10,469	15,974	21,503	27,057	32,636	38,238	43,866	49,518	55,195	60,896	66,622
	40%	5,771	12,040	18,341	24,674	31,039	37,437	43,866	50,327	56,821	63,347	69,904	76,494
	45%	6,553	13,612	20,712	27,853	35,034	42,256	49,518	56,821	64,165	71,549	78,974	86,439
	50%	7,335	15,186	23,088	31,039	39,041	47,093	55,195	63,347	71,549	79,801	88,104	96,456
	55%	8,118	16,762	25,468	34,234	43,061	51,948	60,896	69,904	78,974	88,104	97,294	106,546
	60%	8,901	18,341	27,853	37,437	47,093	56,821	66,622	76,494	86,439	96,456	106,546	116,707
	65%	9,685	19,921	30,242	40,647	51,137	61,712	72,372	83,116	93,945	104,859	115,858	126,941
	70%	10,469	21,503	32,636	43,866	55,195	66,622	78,147	89,770	101,492	113,312	125,230	137,247
	75%	11,254	23,088	35,034	47,093	59,264	71,549	83,946	96,456	109,079	121,815	134,664	147,625
	80%	12,040	24,674	37,437	50,327	63,347	76,494	89,770	103,175	116,707	130,368	144,158	158,075
	85%	12,826	26,262	39,844	53,570	67,442	81,458	95,619	109,925	124,376	138,972	153,712	168,598
	90%	13,612	27,853	42,256	56,821	71,549	86,439	101,492	116,707	132,085	147,625	163,327	179,192
	95%	14,399	29,445	44,672	60,080	75,669	91,439	107,390	123,522	139,835	156,329	173,003	189,859
	100%	15,186	31,039	47,093	63,347	79,801	96,456	113,312	130,368	147,625	165,082	182,740	200,598

Figure 17: Country level NPV scenario outcomes heatmap for Kenya, producer surplus basis

	Kenya (doesn't include research cost)											
	NPV Scenario Heatmap (USD $,000), Total Surplus basis											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	1,401	3,269	5,138	7,008	8,880	10,753	12,627	14,502	16,379	18,257	20,135	22,016
10%	3,269	7,008	10,753	14,502	18,257	22,016	25,779	29,548	33,321	37,100	40,883	44,671
15%	5,138	10,753	16,379	22,016	27,663	33,321	38,991	44,671	50,361	56,063	61,776	67,499
20%	7,008	14,502	22,016	29,548	37,100	44,671	52,261	59,870	67,499	75,147	82,814	90,500
25%	8,880	18,257	27,663	37,100	46,566	56,063	65,590	75,147	84,734	94,351	103,998	113,675
30%	10,753	22,016	33,321	44,671	56,063	67,499	78,978	90,500	102,066	113,675	125,328	137,023
35%	12,627	25,779	38,991	52,261	65,590	78,978	92,425	105,931	119,496	133,120	146,803	160,545
40%	14,502	29,548	44,671	59,870	75,147	90,500	105,931	121,439	137,023	152,685	168,423	184,239
45%	16,379	33,321	50,361	67,499	84,734	102,066	119,496	137,023	154,648	172,370	190,190	208,107
50%	18,257	37,100	56,063	75,147	94,351	113,675	133,120	152,685	172,370	192,176	212,102	232,148
55%	20,135	40,883	61,776	82,814	103,998	125,328	146,803	168,423	190,190	212,102	234,159	256,362
60%	22,016	44,671	67,499	90,500	113,675	137,023	160,545	184,239	208,107	232,148	256,362	280,750
65%	23,897	48,463	73,233	98,206	123,382	148,762	174,345	200,132	226,122	252,315	278,711	305,311
70%	25,779	52,261	78,978	105,931	133,120	160,545	188,205	216,101	244,234	272,602	301,206	330,045
75%	27,663	56,063	84,734	113,675	142,887	172,370	202,124	232,148	262,443	293,009	323,845	354,953
80%	29,548	59,870	90,500	121,439	152,685	184,239	216,101	248,272	280,750	313,537	346,631	380,033
85%	31,434	63,682	96,278	129,221	162,512	196,151	230,138	264,472	299,155	334,184	369,562	405,287
90%	33,321	67,499	102,066	137,023	172,370	208,107	244,234	280,750	317,656	354,953	392,639	430,715
95%	35,210	71,320	107,865	144,844	182,258	220,106	258,388	297,105	336,256	375,841	415,861	456,315
100%	37,100	75,147	113,675	152,685	192,176	232,148	272,602	313,537	354,953	396,850	439,229	482,089

Figure 18: Country level NPV scenario outcomes heatmap for Kenya, total surplus basis

	Tanzania (doesn't include research cost)											
	NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	-162	387	937	1,487	2,038	2,589	3,140	3,692	4,244	4,796	5,349	5,902
10%	387	1,487	2,589	3,692	4,796	5,902	7,009	8,118	9,228	10,340	11,453	12,567
15%	937	2,589	4,244	5,902	7,564	9,228	10,896	12,567	14,241	15,918	17,599	19,283
20%	1,487	3,692	5,902	8,118	10,340	12,567	14,800	17,038	19,283	21,533	23,788	26,049
25%	2,038	4,796	7,564	10,340	13,125	15,918	18,721	21,533	24,353	27,182	30,020	32,867
30%	2,589	5,902	9,228	12,567	15,918	19,283	22,660	26,049	29,452	32,867	36,295	39,736
35%	3,140	7,009	10,896	14,800	18,721	22,660	26,616	30,589	34,579	38,587	42,613	46,655
40%	3,692	8,118	12,567	17,038	21,533	26,049	30,589	35,151	39,736	44,343	48,973	53,626
45%	4,244	9,228	14,241	19,283	24,353	29,452	34,579	39,736	44,921	50,134	55,376	60,647
50%	4,796	10,340	15,918	21,533	27,182	32,867	38,587	44,343	50,134	55,961	61,823	67,720
55%	5,349	11,453	17,599	23,788	30,020	36,295	42,613	48,973	55,376	61,823	68,312	74,843
60%	5,902	12,567	19,283	26,049	32,867	39,736	46,655	53,626	60,647	67,720	74,843	82,018
65%	6,456	13,683	20,970	28,316	35,723	43,189	50,715	58,301	65,947	73,653	81,418	89,243
70%	7,009	14,800	22,660	30,589	38,587	46,655	54,793	62,999	71,275	79,621	88,035	96,520
75%	7,564	15,918	24,353	32,867	41,461	50,134	58,887	67,720	76,632	85,624	94,696	103,847
80%	8,118	17,038	26,049	35,151	44,343	53,626	62,999	72,463	82,018	91,663	101,399	111,225
85%	8,673	18,160	27,749	37,440	47,234	57,130	67,129	77,229	87,432	97,737	108,145	118,655
90%	9,228	19,283	29,452	39,736	50,134	60,647	71,275	82,018	92,875	103,847	114,934	126,135
95%	9,784	20,407	31,158	42,037	53,043	64,177	75,439	86,829	98,347	109,992	121,765	133,666
100%	10,340	21,533	32,867	44,343	55,961	67,720	79,621	91,663	103,847	116,173	128,640	141,248

Figure 19: Country level NPV scenario outcomes heatmap for Tanzania, producer surplus basis

		Tanzania (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Total Surplus basis											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	607	1,925	3,245	4,566	5,887	7,210	8,533	9,857	11,182	12,507	13,834	15,161
Adoption rate	10%	1,925	4,566	7,210	9,857	12,507	15,161	17,819	20,480	23,144	25,811	28,482	31,157
	15%	3,245	7,210	11,182	15,161	19,149	23,144	27,147	31,157	35,175	39,200	43,234	47,275
	20%	4,566	9,857	15,161	20,480	25,811	31,157	36,516	41,888	47,275	52,674	58,088	63,515
	25%	5,887	12,507	19,149	25,811	32,495	39,200	45,927	52,674	59,443	66,233	73,045	79,877
	30%	7,210	15,161	23,144	31,157	39,200	47,275	55,379	63,515	71,681	79,877	88,104	96,362
	35%	8,533	17,819	27,147	36,516	45,927	55,379	64,874	74,409	83,987	93,606	103,266	112,969
	40%	9,857	20,480	31,157	41,888	52,674	63,515	74,409	85,358	96,362	107,420	118,532	129,698
	45%	11,182	23,144	35,175	47,275	59,443	71,681	83,987	96,362	108,806	121,318	133,900	146,550
	50%	12,507	25,811	39,200	52,674	66,233	79,877	93,606	107,420	121,318	135,302	149,370	163,524
	55%	13,834	28,482	43,234	58,088	73,045	88,104	103,266	118,532	133,900	149,370	164,944	180,620
	60%	15,161	31,157	47,275	63,515	79,877	96,362	112,969	129,698	146,550	163,524	180,620	197,839
	65%	16,490	33,835	51,323	68,955	86,731	104,650	122,713	140,919	159,269	177,762	196,399	215,180
	70%	17,819	36,516	55,379	74,409	93,606	112,969	132,498	152,194	172,057	192,086	212,281	232,643
	75%	19,149	39,200	59,443	79,877	100,502	121,318	142,325	163,524	184,913	206,494	228,266	250,229
	80%	20,480	41,888	63,515	85,358	107,420	129,698	152,194	174,908	197,839	220,988	244,354	267,937
	85%	21,811	44,580	67,594	90,853	114,358	138,109	162,105	186,346	210,833	235,566	260,544	285,767
	90%	23,144	47,275	71,681	96,362	121,318	146,550	172,057	197,839	223,896	250,229	276,837	303,720
	95%	24,477	49,973	75,775	101,884	128,299	155,022	182,051	209,386	237,028	264,977	293,233	321,795
	100%	25,811	52,674	79,877	107,420	135,302	163,524	192,086	220,988	250,229	279,810	309,732	339,993

Figure 20: Country level NPV scenario outcomes heatmap for Tanzania, total surplus basis

		Ethiopia (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	1,212	2,844	4,478	6,113	7,749	9,386	11,024	12,663	14,303	15,944	17,586	19,229
Adoption rate	10%	2,844	6,113	9,386	12,663	15,944	19,229	22,519	25,812	29,110	32,413	35,719	39,029
	15%	4,478	9,386	14,303	19,229	24,165	29,110	34,065	39,029	44,003	48,986	53,979	58,981
	20%	6,113	12,663	19,229	25,812	32,413	39,029	45,663	52,314	58,981	65,666	72,367	79,085
	25%	7,749	15,944	24,165	32,413	40,686	48,986	57,313	65,666	74,045	82,450	90,881	99,339
	30%	9,386	19,229	29,110	39,029	48,986	58,981	69,014	79,085	89,193	99,339	109,523	119,745
	35%	11,024	22,519	34,065	45,663	57,313	69,014	80,767	92,571	104,427	116,334	128,293	140,303
	40%	12,663	25,812	39,029	52,314	65,666	79,085	92,571	106,124	119,745	133,434	147,189	161,012
	45%	14,303	29,110	44,003	58,981	74,045	89,193	104,427	119,745	135,149	150,638	166,213	181,872
	50%	15,944	32,413	48,986	65,666	82,450	99,339	116,334	133,434	150,638	167,949	185,364	202,884
	55%	17,586	35,719	53,979	72,367	90,881	109,523	128,293	147,189	166,213	185,364	204,642	224,047
	60%	19,229	39,029	58,981	79,085	99,339	119,745	140,303	161,012	181,872	202,884	224,047	245,362
	65%	20,873	42,344	63,993	85,819	107,823	130,005	152,365	174,902	197,617	220,510	243,580	266,828
	70%	22,519	45,663	69,014	92,571	116,334	140,303	164,478	188,859	213,447	238,240	263,240	288,446
	75%	24,165	48,986	74,045	99,339	124,871	150,638	176,643	202,884	229,362	256,076	283,027	310,215
	80%	25,812	52,314	79,085	106,124	133,434	161,012	188,859	216,976	245,362	274,017	302,942	332,135
	85%	27,461	55,645	84,134	112,926	142,023	171,423	201,127	231,135	261,448	292,063	322,983	354,207
	90%	29,110	58,981	89,193	119,745	150,638	181,872	213,447	245,362	277,618	310,215	343,152	376,430
	95%	30,761	62,321	94,261	126,581	159,280	192,359	225,818	259,656	293,874	328,471	363,448	398,805
	100%	32,413	65,666	99,339	133,434	167,949	202,884	238,240	274,017	310,215	346,833	383,872	421,331

Figure 21: Country level NPV scenario outcomes heatmap for Ethiopia, producer surplus basis

		Ethiopia (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Total Surplus basis											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	3,496	7,414	11,335	15,259	19,185	23,113	27,044	30,978	34,914	38,853	42,794	46,738
Adoption rate	10%	7,414	15,259	23,113	30,978	38,853	46,738	54,633	62,538	70,453	78,378	86,313	94,259
	15%	11,335	23,113	34,914	46,738	58,584	70,453	82,344	94,259	106,196	118,155	130,138	142,143
	20%	15,259	30,978	46,738	62,538	78,378	94,259	110,180	126,141	142,143	158,185	174,268	190,391
	25%	19,185	38,853	58,584	78,378	98,235	118,155	138,139	158,185	178,295	198,467	218,703	239,002
	30%	23,113	46,738	70,453	94,259	118,155	142,143	166,221	190,391	214,651	239,002	263,444	287,977
	35%	27,044	54,633	82,344	110,180	138,139	166,221	194,428	222,758	251,212	279,789	308,490	337,315
	40%	30,978	62,538	94,259	126,141	158,185	190,391	222,758	255,287	287,977	320,828	353,842	387,016
	45%	34,914	70,453	106,196	142,143	178,295	214,651	251,212	287,977	324,946	362,120	399,499	437,081
	50%	38,853	78,378	118,155	158,185	198,467	239,002	279,789	320,828	362,120	403,664	445,461	487,510
	55%	42,794	86,313	130,138	174,268	218,703	263,444	308,490	353,842	399,499	445,461	491,729	538,302
	60%	46,738	94,259	142,143	190,391	239,002	287,977	337,315	387,016	437,081	487,510	538,302	589,457
	65%	50,684	102,214	154,171	206,554	259,364	312,600	366,263	420,353	474,869	529,811	585,180	640,976
	70%	54,633	110,180	166,221	222,758	279,789	337,315	395,335	453,850	512,860	572,365	632,364	692,858
	75%	58,584	118,155	178,295	239,002	300,277	362,120	424,531	487,510	551,056	615,171	679,853	745,103
	80%	62,538	126,141	190,391	255,287	320,828	387,016	453,850	521,331	589,457	658,229	727,648	797,713
	85%	66,494	134,137	202,510	271,611	341,443	412,003	483,294	555,313	628,062	701,540	775,748	850,685
	90%	70,453	142,143	214,651	287,977	362,120	437,081	512,860	589,457	666,871	745,103	824,153	904,021
	95%	74,414	150,159	226,815	304,382	382,861	462,250	542,551	623,762	705,885	788,919	872,864	957,720
	100%	78,378	158,185	239,002	320,828	403,664	487,510	572,365	658,229	745,103	832,987	921,880	1,011,783

Figure 22: Country level NPV scenario outcomes heatmap for Ethiopia, total surplus basis

		Uganda (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
			Increase in productivity										
		5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	1	312	623	934	1,245	1,557	1,869	2,181	2,493	2,805	3,118	3,431
Adoption rate	10%	312	934	1,557	2,181	2,805	3,431	4,057	4,684	5,312	5,941	6,570	7,200
	15%	623	1,557	2,493	3,431	4,370	5,312	6,255	7,200	8,147	9,096	10,046	10,998
	20%	934	2,181	3,431	4,684	5,941	7,200	8,463	9,729	10,998	12,271	13,547	14,826
	25%	1,245	2,805	4,370	5,941	7,516	9,096	10,681	12,271	13,866	15,466	17,071	18,682
	30%	1,557	3,431	5,312	7,200	9,096	10,998	12,908	14,826	16,750	18,682	20,620	22,566
	35%	1,869	4,057	6,255	8,463	10,681	12,908	15,146	17,393	19,650	21,917	24,193	26,480
	40%	2,181	4,684	7,200	9,729	12,271	14,826	17,393	19,973	22,566	25,172	27,791	30,422
	45%	2,493	5,312	8,147	10,998	13,866	16,750	19,650	22,566	25,499	28,447	31,412	34,394
	50%	2,805	5,941	9,096	12,271	15,466	18,682	21,917	25,172	28,447	31,743	35,058	38,394
	55%	3,118	6,570	10,046	13,547	17,071	20,620	24,193	27,791	31,412	35,058	38,728	42,423
	60%	3,431	7,200	10,998	14,826	18,682	22,566	26,480	30,422	34,394	38,394	42,423	46,480
	65%	3,744	7,831	11,953	16,108	20,297	24,519	28,776	33,067	37,391	41,749	46,141	50,567
	70%	4,057	8,463	12,908	17,393	21,917	26,480	31,082	35,724	40,404	45,124	49,884	54,682
	75%	4,370	9,096	13,866	18,682	23,542	28,447	33,398	38,394	43,434	48,520	53,651	58,826
	80%	4,684	9,729	14,826	19,973	25,172	30,422	35,724	41,076	46,480	51,935	57,442	62,999
	85%	4,998	10,363	15,787	21,268	26,807	32,404	38,059	43,772	49,542	55,371	61,257	67,201
	90%	5,312	10,998	16,750	22,566	28,447	34,394	40,404	46,480	52,621	58,826	65,097	71,432
	95%	5,626	11,634	17,715	23,868	30,093	36,390	42,760	49,201	55,716	62,302	68,961	75,692
	100%	5,941	12,271	18,682	25,172	31,743	38,394	45,124	51,935	58,826	65,798	72,849	79,980

Figure 23: Country level NPV scenario outcomes heatmap for Uganda, producer surplus basis

	Uganda (doesn't include research cost)											
	NPV Scenario Heatmap (USD $,000), Total Surplus basis											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	436	1,182	1,928	2,675	3,422	4,170	4,919	5,667	6,417	7,167	7,917	8,668
10%	1,182	2,675	4,170	5,667	7,167	8,668	10,171	11,675	13,182	14,691	16,202	17,714
15%	1,928	4,170	6,417	8,668	10,923	13,182	15,446	17,714	19,987	22,264	24,545	26,830
20%	2,675	5,667	8,668	11,675	14,691	17,714	20,745	23,784	26,830	29,884	32,946	36,015
25%	3,422	7,167	10,923	14,691	18,471	22,264	26,068	29,884	33,712	37,553	41,405	45,269
30%	4,170	8,668	13,182	17,714	22,264	26,830	31,414	36,015	40,634	45,269	49,923	54,593
35%	4,919	10,171	15,446	20,745	26,068	31,414	36,784	42,177	47,594	53,034	58,498	63,986
40%	5,667	11,675	17,714	23,784	29,884	36,015	42,177	48,370	54,593	60,847	67,132	73,447
45%	6,417	13,182	19,987	26,830	33,712	40,634	47,594	54,593	61,631	68,708	75,824	82,978
50%	7,167	14,691	22,264	29,884	37,553	45,269	53,034	60,847	68,708	76,617	84,574	92,579
55%	7,917	16,202	24,545	32,946	41,405	49,923	58,498	67,132	75,824	84,574	93,382	102,248
60%	8,668	17,714	26,830	36,015	45,269	54,593	63,986	73,447	82,978	92,579	102,248	111,986
65%	9,419	19,229	29,120	39,092	49,146	59,281	69,497	79,794	90,172	100,632	111,172	121,794
70%	10,171	20,745	31,414	42,177	53,034	63,986	75,031	86,171	97,405	108,733	120,155	131,671
75%	10,923	22,264	33,712	45,269	56,935	68,708	80,589	92,579	104,676	116,882	129,195	141,617
80%	11,675	23,784	36,015	48,370	60,847	73,447	86,171	99,017	111,986	125,079	138,294	151,633
85%	12,429	25,306	38,322	51,477	64,771	78,204	91,776	105,486	119,336	133,324	147,451	161,717
90%	13,182	26,830	40,634	54,593	68,708	82,978	97,405	111,986	126,724	141,617	156,666	171,871
95%	13,936	28,356	42,949	57,716	72,656	87,770	103,057	118,517	134,151	149,959	165,939	182,094
100%	14,691	29,884	45,269	60,847	76,617	92,579	108,733	125,079	141,617	158,348	175,271	192,386

Figure 24: Country level NPV scenario outcomes heatmap for Uganda, total surplus basis

	Rwanda (doesn't include research cost)											
	NPV Scenario Heatmap (USD $,000), Producer Surplus basis											
		Increase in productivity										
Adoption rate	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
5%	21	77	134	190	247	303	360	416	473	530	587	643
10%	77	190	303	416	530	643	757	871	985	1,099	1,213	1,327
15%	134	303	473	643	814	985	1,156	1,327	1,499	1,671	1,844	2,017
20%	190	416	643	871	1,099	1,327	1,557	1,786	2,017	2,248	2,479	2,711
25%	247	530	814	1,099	1,385	1,671	1,959	2,248	2,537	2,827	3,119	3,411
30%	303	643	985	1,327	1,671	2,017	2,363	2,711	3,060	3,411	3,763	4,116
35%	360	757	1,156	1,557	1,959	2,363	2,769	3,177	3,587	3,998	4,411	4,826
40%	416	871	1,327	1,786	2,248	2,711	3,177	3,645	4,116	4,589	5,064	5,542
45%	473	985	1,499	2,017	2,537	3,060	3,587	4,116	4,648	5,183	5,721	6,262
50%	530	1,099	1,671	2,248	2,827	3,411	3,998	4,589	5,183	5,781	6,383	6,988
55%	587	1,213	1,844	2,479	3,119	3,763	4,411	5,064	5,721	6,383	7,049	7,719
60%	643	1,327	2,017	2,711	3,411	4,116	4,826	5,542	6,262	6,988	7,719	8,456
65%	700	1,442	2,190	2,944	3,704	4,470	5,243	6,021	6,806	7,597	8,394	9,197
70%	757	1,557	2,363	3,177	3,998	4,826	5,661	6,504	7,353	8,210	9,073	9,944
75%	814	1,671	2,537	3,411	4,293	5,183	6,082	6,988	7,903	8,826	9,757	10,696
80%	871	1,786	2,711	3,645	4,589	5,542	6,504	7,475	8,456	9,446	10,445	11,453
85%	928	1,901	2,886	3,880	4,886	5,901	6,927	7,964	9,011	10,069	11,137	12,216
90%	985	2,017	3,060	4,116	5,183	6,262	7,353	8,456	9,570	10,696	11,834	12,984
95%	1,042	2,132	3,235	4,352	5,482	6,624	7,780	8,949	10,132	11,327	12,535	13,757
100%	1,099	2,248	3,411	4,589	5,781	6,988	8,210	9,446	10,696	11,961	13,241	14,535

Figure 25: Country level NPV scenario outcomes heatmap for Rwanda, producer surplus basis

Rwanda (doesn't include research cost)

NPV Scenario Heatmap (USD $,000), Total Surplus basis

Adoption rate	Increase in productivity →	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	100	235	371	506	642	778	913	1,049	1,185	1,321	1,457	1,594
	10%	235	506	778	1,049	1,321	1,594	1,866	2,140	2,413	2,687	2,961	3,235
	15%	371	778	1,185	1,594	2,003	2,413	2,824	3,235	3,648	4,061	4,475	4,890
	20%	506	1,049	1,594	2,140	2,687	3,235	3,785	4,337	4,890	5,444	5,999	6,556
	25%	642	1,321	2,003	2,687	3,373	4,061	4,751	5,444	6,139	6,836	7,535	8,236
	30%	778	1,594	2,413	3,235	4,061	4,890	5,722	6,556	7,395	8,236	9,080	9,928
	35%	913	1,866	2,824	3,785	4,751	5,722	6,696	7,675	8,658	9,645	10,636	11,632
	40%	1,049	2,140	3,235	4,337	5,444	6,556	7,675	8,798	9,928	11,063	12,203	13,349
	45%	1,185	2,413	3,648	4,890	6,139	7,395	8,658	9,928	11,205	12,489	13,781	15,079
	50%	1,321	2,687	4,061	5,444	6,836	8,236	9,645	11,063	12,489	13,924	15,368	16,821
	55%	1,457	2,961	4,475	5,999	7,535	9,080	10,636	12,203	13,781	15,368	16,967	18,576
	60%	1,594	3,235	4,890	6,556	8,236	9,928	11,632	13,349	15,079	16,821	18,576	20,343
	65%	1,730	3,510	5,305	7,115	8,939	10,778	12,632	14,501	16,384	18,282	20,195	22,123
	70%	1,866	3,785	5,722	7,675	9,645	11,632	13,637	15,658	17,697	19,753	21,825	23,915
	75%	2,003	4,061	6,139	8,236	10,353	12,489	14,645	16,821	19,016	21,231	23,466	25,720
	80%	2,140	4,337	6,556	8,798	11,063	13,349	15,658	17,989	20,343	22,719	25,117	27,538
	85%	2,276	4,613	6,975	9,362	11,775	14,213	16,675	19,163	21,677	24,215	26,779	29,368
	90%	2,413	4,890	7,395	9,928	12,489	15,079	17,697	20,343	23,018	25,720	28,451	31,210
	95%	2,550	5,167	7,815	10,495	13,206	15,948	18,723	21,528	24,365	27,234	30,134	33,065
	100%	2,687	5,444	8,236	11,063	13,924	16,821	19,753	22,719	25,720	28,756	31,827	34,933

Figure 26: Country level NPV scenario outcomes heatmap for Rwanda, total surplus basis

Burundi (doesn't include research cost)

NPV Scenario Heatmap (USD $,000), Producer Surplus basis

Adoption rate	Increase in productivity →	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%
	5%	-1	6	14	22	30	38	46	54	62	69	77	85
	10%	6	22	38	54	69	85	101	117	133	149	165	181
	15%	14	38	62	85	109	133	157	181	204	228	252	276
	20%	22	54	85	117	149	181	212	244	276	309	341	373
	25%	30	69	109	149	188	228	268	309	349	389	430	471
	30%	38	85	133	181	228	276	325	373	422	471	520	569
	35%	46	101	157	212	268	325	381	438	495	552	610	668
	40%	54	117	181	244	309	373	438	503	569	635	701	767
	45%	62	133	204	276	349	422	495	569	643	717	792	868
	50%	69	149	228	309	389	471	552	635	717	801	884	969
	55%	77	165	252	341	430	520	610	701	792	884	977	1,071
	60%	85	181	276	373	471	569	668	767	868	969	1,071	1,173
	65%	93	196	301	406	511	618	726	834	943	1,053	1,164	1,276
	70%	101	212	325	438	552	668	784	901	1,020	1,139	1,259	1,380
	75%	109	228	349	471	593	717	842	969	1,096	1,225	1,354	1,485
	80%	117	244	373	503	635	767	901	1,036	1,173	1,311	1,450	1,590
	85%	125	260	397	536	676	817	960	1,105	1,250	1,398	1,546	1,697
	90%	133	276	422	569	717	868	1,020	1,173	1,328	1,485	1,643	1,804
	95%	141	293	446	602	759	918	1,079	1,242	1,406	1,573	1,741	1,911
	100%	149	309	471	635	801	969	1,139	1,311	1,485	1,661	1,839	2,020

Figure 27: Country level NPV scenario outcomes heatmap for Burundi, producer surplus basis

		Burundi (doesn't include research cost)											
		NPV Scenario Heatmap (USD $,000), Total Surplus basis											
			Increase in productivity										
		5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**	**55%**	**60%**
Adoption rate	**5%**	10	28	47	66	85	104	123	142	161	180	199	218
	10%	28	66	104	142	180	218	256	294	332	370	408	446
	15%	47	104	161	218	275	332	389	446	504	561	619	677
	20%	66	142	218	294	370	446	523	600	677	754	831	909
	25%	85	180	275	370	465	561	657	754	850	947	1,045	1,142
	30%	104	218	332	446	561	677	792	909	1,025	1,142	1,260	1,378
	35%	123	256	389	523	657	792	928	1,064	1,201	1,339	1,477	1,615
	40%	142	294	446	600	754	909	1,064	1,221	1,378	1,536	1,695	1,854
	45%	161	332	504	677	850	1,025	1,201	1,378	1,556	1,735	1,914	2,095
	50%	180	370	561	754	947	1,142	1,339	1,536	1,735	1,935	2,136	2,338
	55%	199	408	619	831	1,045	1,260	1,477	1,695	1,914	2,136	2,358	2,582
	60%	218	446	677	909	1,142	1,378	1,615	1,854	2,095	2,338	2,582	2,828
	65%	237	484	734	986	1,240	1,496	1,755	2,015	2,277	2,541	2,808	3,076
	70%	256	523	792	1,064	1,339	1,615	1,894	2,176	2,460	2,746	3,035	3,326
	75%	275	561	850	1,142	1,437	1,735	2,035	2,338	2,644	2,952	3,263	3,577
	80%	294	600	909	1,221	1,536	1,854	2,176	2,501	2,828	3,159	3,493	3,830
	85%	313	638	967	1,299	1,635	1,975	2,318	2,664	3,014	3,367	3,724	4,085
	90%	332	677	1,025	1,378	1,735	2,095	2,460	2,828	3,201	3,577	3,957	4,341
	95%	351	715	1,084	1,457	1,834	2,216	2,603	2,993	3,388	3,788	4,192	4,600
	100%	370	754	1,142	1,536	1,935	2,338	2,746	3,159	3,577	4,000	4,427	4,860

Figure 28: Country level NPV scenario outcomes heatmap for Burundi, total surplus basis

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