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Research Paper

Got forages? Understanding potential returns on investment in *Brachiaria* spp. for dairy producers in Eastern Africa

Comprender los retornos potenciales de la inversión en Brachiaria *spp. para los productores de leche en el Este de África*

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Abstract

Production of livestock and dairy products in Sub-Saharan Africa struggles to keep 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 6 Eastern African countries using an economic surplus model. Results are presented across a range of potential scenarios involving different adoption rates and percentage increases in production. For all but the lowest levels of adoption and production 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 production necessary to achieve specific desired levels of net benefit. Overall, the model output suggests that investment in a forages research program related to the qualities of the forage itself as well as programs to enhance dissemination and adoption of new materials would be low risk and have high likelihood for positive outcomes, generating discounted net benefits in the order of multiple tens of millions of dollars over a 30-year time horizon.

Keywords: Climate change adaptation, ex-ante impact assessment, producer surplus, tropical forages.

Resumen

La producción pecuaria, incluyendo la láctea, en África subsahariana exige un alto esfuerzo para mantenerse al ritmo de la creciente demanda. No obstante existe la posibilidad de cerrar esta brecha de una manera amigable con el clima mediante la introducción de variedades de forrajeras mejoradas del género *Brachiaria*. En el estudio se evaluó el potencial impacto económico del desarrollo y liberación de estas variedades en 6 países de África Oriental utilizando un modelo de excedentes económicos. Los resultados se presentan a través de un rango potencial de escenarios que implican diferentes tasas de adopción e incrementos porcentuales de producción. Para todos ellos, excepto los niveles más bajos de adopción y aumento de producción, los forrajes mejorados tienen el potencial de un retorno positivo en la inversión. Usando estos resultados, presentamos fórmulas que ayudan a los investigadores a calcular la tasa de adopción o aumento porcentual de la producción necesaria para lograr niveles deseados de beneficio neto. En general, el resultado del modelo sugiere que la inversión en un programa de investigación de forrajes y programas básicos de diseminación y adopción de nuevos materiales es de bajo riesgo y con alta probabilidad de obtener resultados positivos, generando beneficios netos en el orden de varias decenas de millones de dólares sobre un horizonte temporal de 30 años.

Palabras clave: Adaptación al cambio climático, evaluación de impacto ex-ante, excedentes económicos, forrajes tropicales.

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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 (Thornton et al. 2007; FAO 2009; Thornton 2010; Robinson and Pozzi 2011; Ghimire et al. 2015). Supply of livestock products has not kept pace with demand, due primarily to low productivity and limited land area (Rakotoarisoa et al. 2011). Production of livestock products is further complicated by climate change (Thornton et al. 2007; Thornton 2010). 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, rain-fed crop-livestock systems are particularly constrained by a shortage of feed resources during dry seasons, a situation that is systematically aggravated by increasing pressures from climate change and variability (Dzowela 1990; Thornton 2010; Rakotoarisoa et al. 2011).

Better use of the natural resource base offers tremendous potential to increase livestock production in the region (FAO 2009; Ghimire et al. 2015). Research programs such as 'Climate-smart *Brachiaria*' have begun developing strategies to tap into this potential (Djikeng et al. 2014). Such efforts are built around the development of drought-resistant *Brachiaria* grass varieties with climate change-mitigating properties (Ghimire et al. 2015; Maass et al. 2015). Building on our earlier work (González et al. 2016), in this study we present an ex-ante assessment of the potential welfare impacts of increasing milk production by introducing such technology to mixed rainfed crop-livestock systems (Table 1; Figure 3A) in Eastern Africa, using the economic surplus method previously described by Alston et al. (1995).

Brachiaria *technology and milk production*

The genus *Brachiaria* 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 savanna 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 (Jank et al. 2014; Ghimire et al. 2015).

The widespread appeal of *Brachiaria* lies in a diverse set of traits, depending on species and cultivar, including adaptability to infertile and acidic soils, resistance to drought, tolerance of shade and flooding and 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 and Kerridge 1996; Rao et al. 1996; Subbarao et al. 2009; Rao 2014).

The success of *Brachiaria* in other parts of the world has motivated concerted efforts to introduce higher-performing, improved cultivars in Africa. The *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 to 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 (Maass et al. 2015). Much of this diffusion is associated with the spread of 'climate-adapted push-pull'

Table 1. Seré and Steinfeld classification of livestock systems (Robinson et al. 2011). The systems marked with an asterisk are predominant in Eastern Africa.

Acronym	Description
*LGA	Livestock only, rangeland based, arid/semi-arid
*LGH	Livestock only, rangeland based, humid/subhumid
*LGT	Livestock only, rangeland based, temperate/tropical highlands
*MRA	Mixed crop and livestock, rainfed, arid/semi-arid
*MRH	Mixed crop and livestock, rainfed, humid/subhumid
*MRT	Mixed crop and livestock, rainfed, temperate/tropical highlands
LGY	Livestock only, rangeland based, hyper-arid
MIA	Mixed crop and livestock, irrigated, arid/semi-arid
MIH	Mixed crop and livestock, irrigated, humid/sub-humid
MIT	Mixed crop and livestock, irrigated, temperate/tropical highlands
MRY	Mixed crop and livestock, rainfed, hyper-arid

farming systems (Midega et al. 2015). Based on estimates of seed sales, as of 2014, some 1,000 hectares of these hybrids were under cultivation in various African countries, primarily in East Africa (Maass et al. 2015).

While initial results of crop trials demonstrate a potential for positive return on investment (Kabirizi et al. 2013; Ghimire et al. 2015), 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 scaled up significantly (Maass et al. 2015).

A Swedish-funded program called 'Climate-Smart *Brachiaria* Grasses for Improving Livestock Production in East Africa' (referred to as 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 (ILRI) 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 planned future expansion in Eastern Africa and beyond.

In advance of the CSB program, 10 *Brachiaria* cultivars – mostly from the *brizantha* species, but also including the hybrids Mulato and Mulato II – were tested in greenhouses at CIAT in Colombia against Eastern African baseline varieties such as Rhodes and Napier grass. Results were encouraging and, beginning in 2013, 8 of 10 cultivars were selected for field trials at multiple sites in Kenya and Rwanda. Of these 8 cultivars, *B. brizantha* cvv. Piatã, Marandu, La Libertad (also known as MG-4) and Toledo (also known as Xaraés), *B. decumbens* cv. Basilisk and the hybrid Mulato II emerged as the best performing varieties. Mulato II and Marandu were subsequently removed from trials after they proved susceptible to local pest infestation. On-farm evaluation of the remaining 4 cultivars began in 2014 and is ongoing at the time of this study (Ghimire et al. 2015; CSB 2016).

CSB trials also included a focus on the quality of the grass as animal feed. Preliminary data from recent trials indicate that adoption of these mostly *B. brizantha* cultivars has the potential to increase baseline milk production of 3–5 L/cow/d on participating farms in Kenya by 15–40%. A farm trial in Rwanda reported a 30% increase in milk production and a 20% increase in meat production (CSB 2016). No meat production data were available from the Kenya trials.

Brachiaria grasses tend to be drought-resistant and resilient in infertile soils, and produce well with relatively low levels of fertilizer inputs. They are also resistant to many diseases affecting baseline varieties in Eastern Africa, particularly Napier stunt and smut disease (Ghimire et al. 2015; Maass et al. 2015). *Brachiaria* production can be further enhanced by intercropping with deep-rooted, nitrogen-fixing legumes such as Centro and Clitoria (Kabirizi et al. 2013), which themselves are useful sources of nutrition for animals.

Though the dry matter yields of the *Brachiaria* forages under evaluation tend to be lower than those of baseline varieties found in Eastern Africa, their leaf areas are relatively larger, effectively increasing palatability and nutrition per unit of dry matter. The protein concentration of *Brachiaria*, ranging from 8 to 17% at harvest, remains stable for a relatively long time as compared with that of baseline varieties, where protein concentration diminishes after about 4 months (CSB 2016). Surplus *Brachiaria* not immediately consumed can thus be dried and conserved as hay for sale or future use.

The advantages and disadvantages of improved *Brachiaria* grasses relative to baseline varieties also tend 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 should thus consider the opportunity cost in terms of potential forgone revenue from the cash crop.

As of May 2016, at least 4,000 farmers in Kenya and Rwanda had reported planting one of the *Brachiaria* cultivars under CSB evaluation (CSB 2016). Experts at CIAT report that participating farmers appear to prefer *B. brizantha* cv. Piatã of the 4 cultivars currently under CSB evaluation (J. A. Cardoso pers. comm.). The already substantial numbers of farmers using the technology and the corresponding return on investment and increased resilience for the forage systems suggest that there is substantial potential for impact of these forages in Eastern Africa. Using data collected from a number of sources, we evaluate, ex-ante, the potential impact of improved forages in the region.

Modelling the plausible outcome space

In every ex-ante impact study, there is an implicit tradeoff between the accuracy of model parameterization and the time and budget within which this can reasonably be accomplished. In the vein of demand-driven modelling (Antle et al. 2017), we aim not to maximize accuracy, but rather to maximize accuracy subject to the constraints and needs of the stakeholders motivating the study. These stakeholders include a variety of public and private sector actors, all of whom are ultimately motivated by the needs of smallholder farmers who are the end users of the research product. Considering that order-of-magnitude accuracy is often a sufficient premise on which to base policy decisions, and that stakeholders need assessments of potential impact in a timely manner, we take a parsimonious approach based on existing data and consultations with regional experts. We present our modelled outputs not as a final conclusion, but as a map of plausible outcomes intended to aid readers in their navigation towards a conclusion based on their own understandings of forage systems. We further distill this map into a single envelope equation by which the reader can easily generate model outputs for any level of impact, adoption rate and production increase he/she wishes to consider. Finally, we conduct sensitivity analysis on several key parameters.

The Model

When assessing return on investment in research products, the whole process from research outcomes through release and uptake of the new agricultural technology must be considered. The economic benefit for each country in the study area is thus defined as the net present value (NPV) of the cost-benefit stream extending from year one of research up to the point where the adoption ceiling is reached. Program-level costs occur from the initial year of research until release of the new technology. Subsequent costs associated with production of planting materials, marketing and distribution are typically incurred by private sector actors and thus excluded from the calculation, although we do account for minimal country-level diffusion costs incurred by public sector actors from the year of release over an initial phase of adoption.

The tool we use to calculate the benefit stream is Alston et al.'s (1995) economic surplus model for closed economies. This model, summarized in Figure 1, measures benefits in a given year as the increase in total surplus resulting from a research-induced shift in the supply curve for a given commodity of interest (the shaded area). The total surplus can be divided further into benefits accruing to producers (producer surplus, the shaded area above line P_1b) and benefits accruing to consumers (consumer surplus, the shaded area below line P_1b).

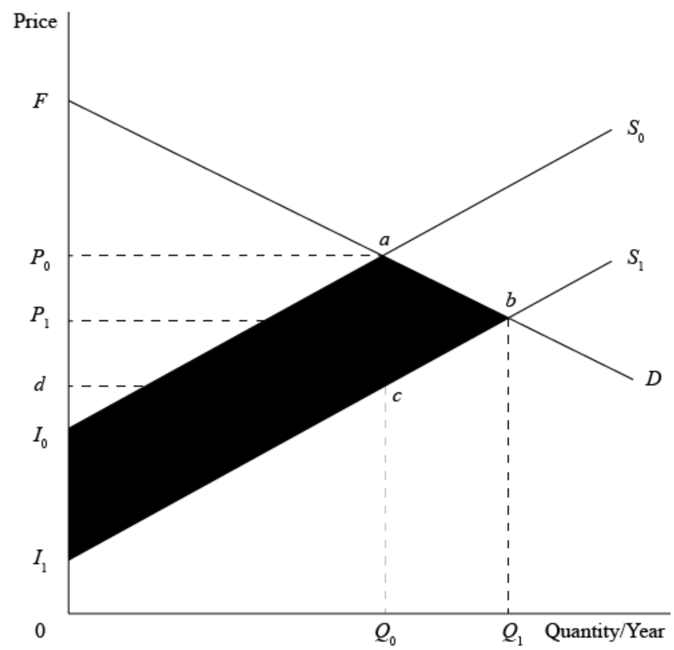

Figure 1. Conceptual representation of the economic surplus model for closed economies (Alston et al. 1995). For a given year in a given market, uptake of the new technology results in higher production and hence a supply curve shift from S_0 to S_1, giving the increase in total surplus I_0abI_1.

The commodity of interest for this study is fresh cows' milk. We evaluate one such model for each country in the study zone, for each year from release of the technology to the year of maximum adoption. The markets are said to be 'closed' because we assume no cross-border trade of fresh milk. Note that these benefit streams understate the true benefit to some degree since they take no account of positive impacts on meat production, which as stated earlier were 20% increases in Rwanda.

Model parameters

In order to calculate the cost stream and the total surplus represented by the shaded area in Figure 1, we require as input the parameters in Table 2. As in most economic surplus studies, estimates of the supply and demand elasticities for the precise commodity and geographical area in question are difficult to acquire. We set the milk supply and demand elasticities to 0.7 and -0.5, respectively, in accordance with an estimate for all of Sub-Saharan Africa obtained by Elbasha et al. (1999). The research time horizon, annual research cost and depreciation factor were set based on consultation with a breeding expert (M. Peters pers. comm.). Based on the success of past CIAT forage research programs for release in other parts of the world, we feel justified in setting the probability of success at 80%. We set the interest rate at 10% to reflect the opportunity cost of not investing the research funds in a stock portfolio of comparable risk.

Table 2. Economic surplus model parameters.

Parameter	Value
Elasticity of milk supply	0.7
Elasticity of milk demand	-0.5
Increase in production (%)	15–40
Increase in variable costs (%)	0
Probability of success (%)	80
Depreciation factor	1
Discount rate (%)	10
Length of research period (yr)	10
Length of uptake period (yr)	20
Length of diffusion period (yr)	8
Annual diffusion costs	$0.10\ N_{MR}^{0.97}$*
Annual research costs (M USD)	1.5
Adoption rate (%)	5–100

*N_{MR} = the number of cattle in mixed rainfed systems.

As discussed earlier, preliminary trial results suggest that adoption of the new technology can increase cow milk production by 15–40%. Another key advantage of the improved varieties is that they are robust on infertile soils, which implies a decrease in the variable costs associated with fertilizer applications. We assume that this potential cost decrease will be insignificant in Eastern Africa, where fertilizer use is already notoriously low.

On the other hand, as mentioned in the same section, many smallholder farmers who introduce the new technology in a complementary role may have to displace a cash crop, thus incurring an opportunity cost in the form of forgone revenue. However, the new technology is most likely to appeal to mixed rainfed smallholder systems within the study zone, where soils are marginal and where opportunity costs are, consequently, low.

For this study, we therefore assume that, on average, the potential variable cost reductions and opportunity costs associated with the new technology would either be negligible or offsetting, resulting in a percentage change in variable costs equal to zero.

Fixed capital costs associated with adoption of the new technology are not accounted for in this model.

After release of the new technology, it is typically acquired by a private sector actor which then accepts any subsequent costs associated with marketing and diffusion. We exclude these costs from our calculation of NPV since they are not incurred by the research institution nor governments. Nonetheless, as a conservative measure, we do include a minimal yearly diffusion cost to public sector actors for the period of initial release and uptake, modelled as a marginally diminishing function of the target industry size. The target industry size is measured as the number of cattle in the country's mixed, rainfed crop-livestock systems (N_{MR}). The parameter values 0.10 and 0.97 in Table 2 are chosen because they generate diffusion cost magnitudes commensurate with the types of promotional, training and outreach activities that are typical of country-level diffusion efforts in the study area. The diffusion cost magnitudes produced by this formula are presented for each country in Table 3. Though diffusion costs reflect an approximate cost based on industry size, they do not specifically take into account the nuances of the technology adoption environment in each country.

Table 3. Diffusion costs per year (USD) and industry size.

Country	Diffusion costs/yr	Industry size[1] (M head)
Kenya	$ 664,134	10.80
Tanzania	$ 860,151	14.09
Ethiopia	$ 2,535,517	42.96
Uganda	$ 481,597	7.75
Rwanda	$ 73,010	1.11
Burundi	$ 23,129	0.34

[1]Sum of total cattle in mixed rainfed systems in Table 8.

Regional expert survey: The technology adoption environment

Technology adoption varies depending on a number of factors and local conditions. Adoption of the new *Brachiaria* technology is modelled using a logistic curve (see Alston et al. 1995 for details). This 2 parameter curve reflects the typical slow rate of adoption initially, followed by a period of rapid diffusion, and then a tapering off of uptake as the adoption rate ceiling is reached (Figure 2). The curve parameters are calculated based on the duration of the uptake period.

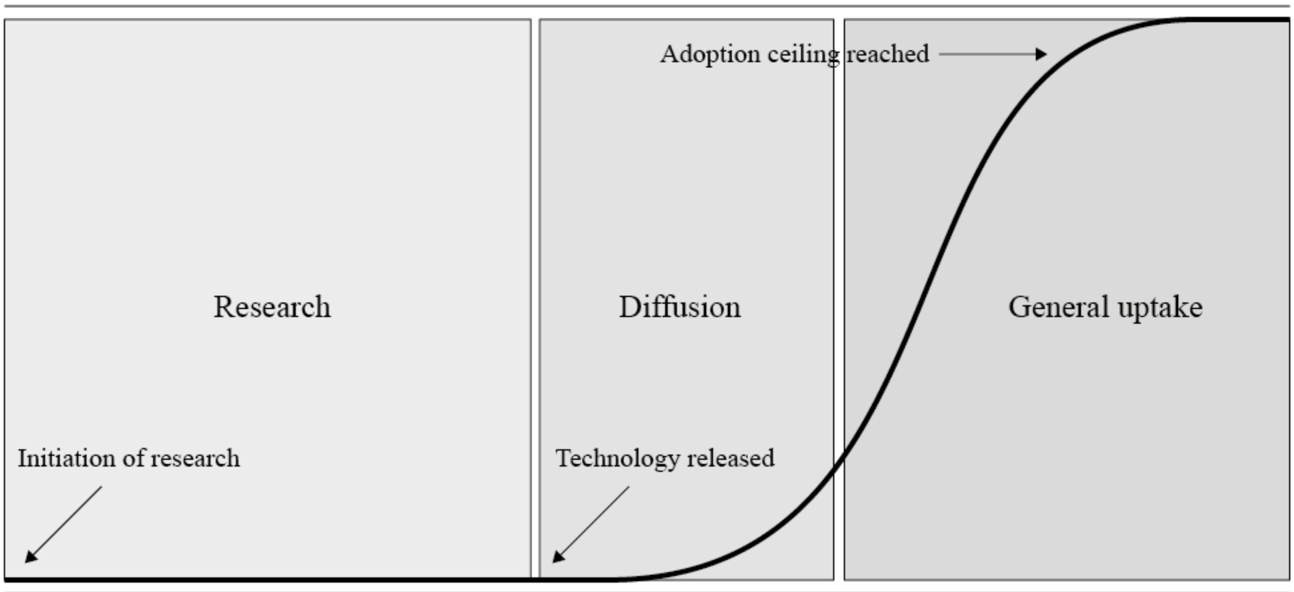

Figure 2. Conceptual illustration of the logistic technology adoption curve.

In order to assess local conditions influencing technology adoption, we sent questionnaires to regional experts in the study zone. The responses we received, summarized in Tables 4–6, confirm that the *Brachiaria* cultivars under evaluation are most likely to appeal to mixed, rainfed systems. They convey moderate optimism about technology uptake in these systems, but also acknowledge considerable impediments, e.g. access to finance, quality inputs and extension services and infrastructure, which may hamper diffusion and uptake of the new technology. For these reasons, rather than present results for a single rate, we present outcomes for all adoption rate levels (at 5% intervals), giving the reader freedom to examine the outcomes that seem most likely to him/her based on his/her own experience and interpretation of the survey responses made available here.

Most respondents indicated a moderate to 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 overall uptake period, including the diffusion period, would last 20 years in all countries.

Table 4. Field expert opinion on adoption rate, diffusion time and effectiveness, and access to finance.
(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[1]	3	2[2]	2[3]	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 finance *(1 = none, 5 = easily accessible)*	NR	2	4	3	5	NR

[1]No response.
[2]Respondent gave a verbal response – 'modest' – which we have interpreted numerically as 2.
[3]Respondent gave an actual adoption rate – 25% – which we have assigned a scale rating of 2.

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

Production system[1]	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	NR[2]	2	1	2	NA[3]	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

[1]For meaning of acronyms, see Table 1. [2]No response. [3]Not applicable.

Table 6. Field expert opinion on most significant current constraints on milk production.

Country	Constraints
Kenya	No response received
Tanzania	• Lack of national dairy herd • Shortage of year-round availability of quality feeds • Inadequate dairy technology and agribusiness skills
Ethiopia	• Poor economic capacity (capital, land, labor) to absorb package of livestock and 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 of inputs and investments in livestock enterprise • Poor quality inputs • Competition for feedstuff resources between humans and livestock • Some of the policies, especially regarding 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 mixtures • 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 of knowledge on suitable forage cultivars, agronomic management practices, conservation and utilization • Farmers' inaccessibility to appropriate forage technologies and technical information
Rwanda	• Physiological constraints: pest problem • Biotic: Napier stunt and smut disease • Abiotic: drought and nutrient deficiency in the soil and aluminum soil toxicity • Environmental constraints: inadequate feed quantity and quality all year round
Burundi	No response received

Producer prices

In addition to the parameters summarized above, contemporary producer prices are required in order to calculate the total surplus stream. These were obtained both from regional experts in the study zone and from FAO. While neither of these sources on its own offered complete price data for all countries involved in this study, together they provide a more robust picture.

FAO 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 3 countries.

Field experts provided price data for Tanzania, Ethiopia, Uganda and Rwanda. In order to be consistent with the prices obtained from FAOSTAT, we again use the 2010–2012 average for these countries, except

Uganda. The Uganda respondent reported prices for only years 2013–2015, so the Uganda producer milk price is averaged over this period. Respondents reported prices in local currency per kilogram, so we converted these prices to USD per metric tonne (MT) using historical exchange rates retrieved for 15 June in each respective year.

For Rwanda and Ethiopia, price data were available from both FAOSTAT and local experts. In these cases we used the lesser of the 2 prices. No price data were obtained for Burundi from any source, so we set Burundi's producer price equivalent to that found in Rwanda.

Table 7. Producer milk prices (USD/MT).

Country	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)

Source: Authors' calculations using input from field experts and FAO data (2015a).

Quantity of production affected

The final piece of information required for calculation of the total surplus area depicted in Figure 1 (p. 120) is the quantity of production affected by the new technology. This is 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 forage varieties currently fail to generate a sufficient feed supply during dry seasons (An Notenbaert pers. comm.). Under the Seré and Steinfeld classification map in Figure 3A, these production systems are designated as MRA, MRH and MRT (see Table 1 for definitions) (Robinson et al. 2011). These systems are characterized by their small size and marginal soils.

Baseline cow milk production data are available from FAO at the country level, but the production system levels defined by Seré and Steinfeld cut across national boundaries. In order to obtain a baseline production figure for each production system within each country, we first calculate the number of cattle within each system within

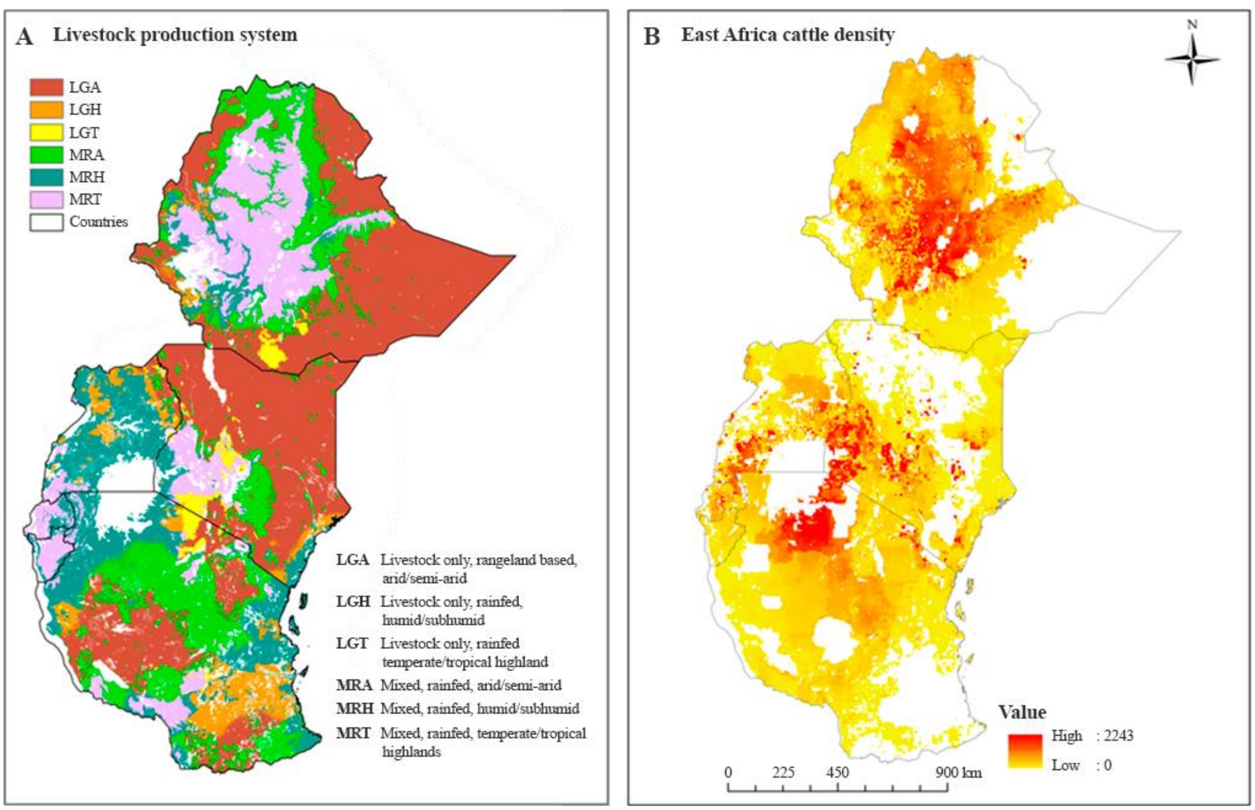

Figure 3. A) Production systems map of the study area. Source: Authors' creation using the production systems map data v 5.0 (FAO and ILRI 2011); **B)** Cattle density map of the study area. Source: Authors' creation using the Gridded Livestock of the World map data v 2.01 (FAO 2010).

each country by overlaying a production system map (Figure 3A) onto the latest available cattle density map (Figure 3B) to give the numbers presented in Table 8. We then generate modelled estimates of milk production for each system within each country as a function of total cattle based on the empirical relationships observed in Figure 4.

Table 8. Calculated number of cows disaggregated by production system in 2010.

Production system[1]	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	4,116,976	1,223,012	3,322,170	241,273	0	0
LGH	284,307	564,216	121,460	1,086,028	0	0
LGT	702,903	50,289	258,146	102,367	0	0
LGY	561	3,669	0	0	0	0
MIA	61,238	75,888	245,343	0	0	0
MIH	78,049	24,176	4,296	5,223	5,613	7,350
MIT	222,326	3,972	803,015	1,677	7,286	2,733
MRA	2,125,379	6,013,215	9,432,923	109,421	0	0
MRH	2,365,977	6,196,315	2,118,675	6,413,741	265,964	47,738
MRT	6,303,699	1,869,350	31,407,804	1,227,967	842,509	291,155
MRY	706	15,504	0	0	0	0
Other	1,022,597	1,647,486	2,008,340	2,531,685	129,776	185,255
Urban	394,850	841,544	595,027	80,244	43,232	8,995
Total	17,679,567	18,528,635	50,317,198	11,799,625	1,294,381	543,226

[1]For meaning of acronyms, see Table 1.

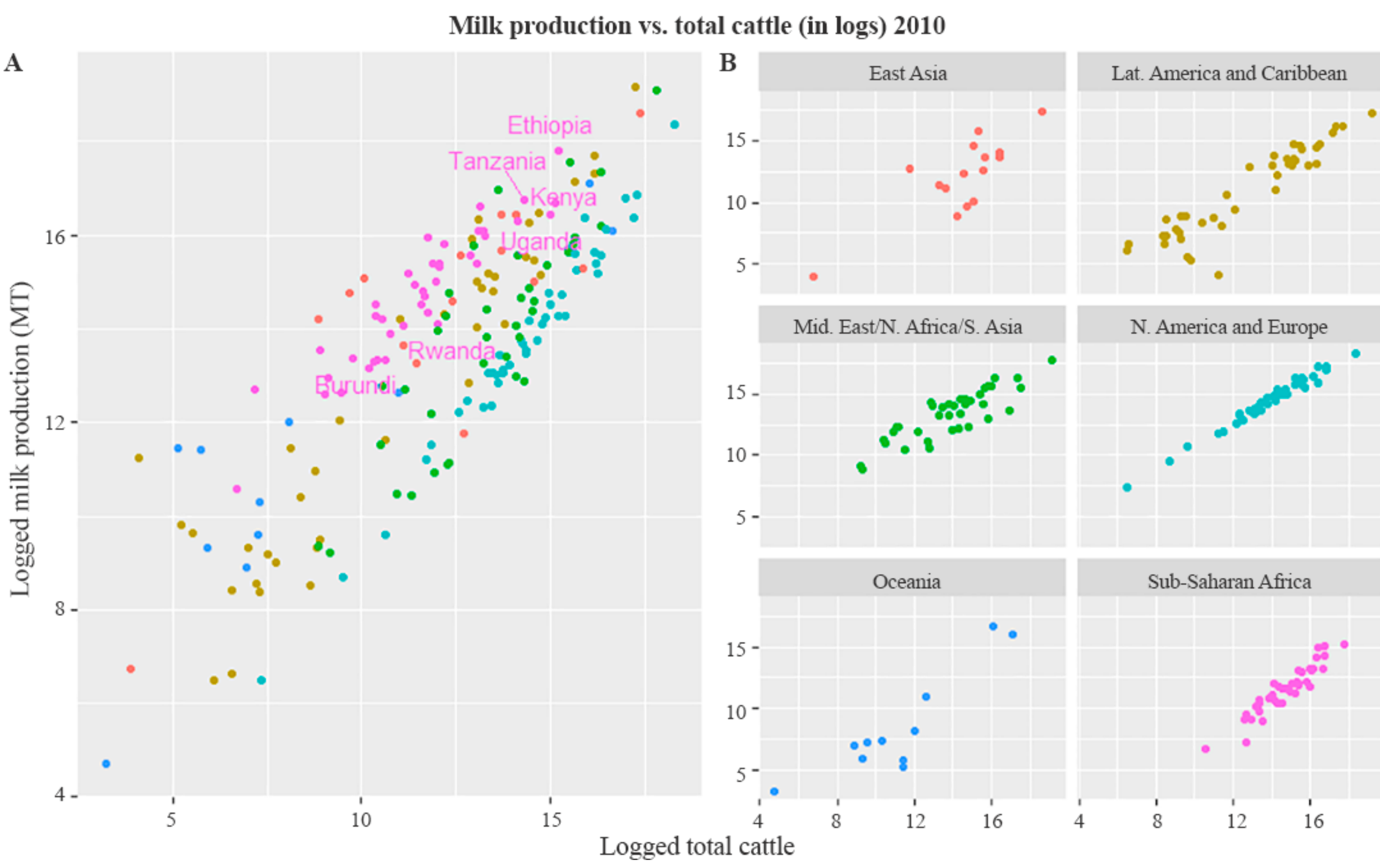

Figure 4. 2010 Milk production plotted against total cattle in logs: **A)** for all countries in the world; and **B)** in separate plots by region. Source: Authors' creation using FAO data (2015b; 2015c)**.**

Figure 4A suggests that a log-linear relationship exists between total cattle and production, but that the y-intercept varies by region. This is drawn out more explicitly in Figure 4B, where regions are plotted separately.

Plots for other years in the FAO database exhibit the same log-linear relationship. In Figure 5, we see that the parameter values for this relationship are stable – albeit over the time periods 1961–2001 and 2006–2014, with a transition period in between[1]. For a reasonable approximation, we conclude that, for a given region, the following scale invariant relationship exists between milk production (P) and total cattle (N).

$$\ln P \approx \alpha \ln N + \beta + \epsilon \qquad \text{Eq. 1}$$

where: for the Sub-Saharan Africa region, the mean values of α and β over 2006–2014 are 1.23 and -6.563 (with standard deviations 0.01 and 0.152), respectively.

Since the relationship is scale invariant, we then apply this model (Equation 1) to the 2010 calculated numbers of cattle per production system within each country (Table 8) to determine milk production at the production system level. We fit parameters α and β for each country such that they are close to their region-wide means of 1.23 and -6.563 above, and such that the total production in each country adds up to within 10% of the corresponding FAO 2010 country level totals. For most countries in the study zone, this results in values for α and β that fall within 2 or 3 standard deviations of the region-wide means, although for Kenya and Rwanda the values are 4 standard deviations from the means (still reasonably close considering that the standard deviations are very small). These modelled approximations of baseline milk production at the production system level are presented for each country in Table 9. Finally, in each country we add up the modelled production in the mixed rainfed production systems. These figures (the 'MR Subtotal' in Table 9) represent the baseline production potentially affected by the new *Brachiaria* technology.

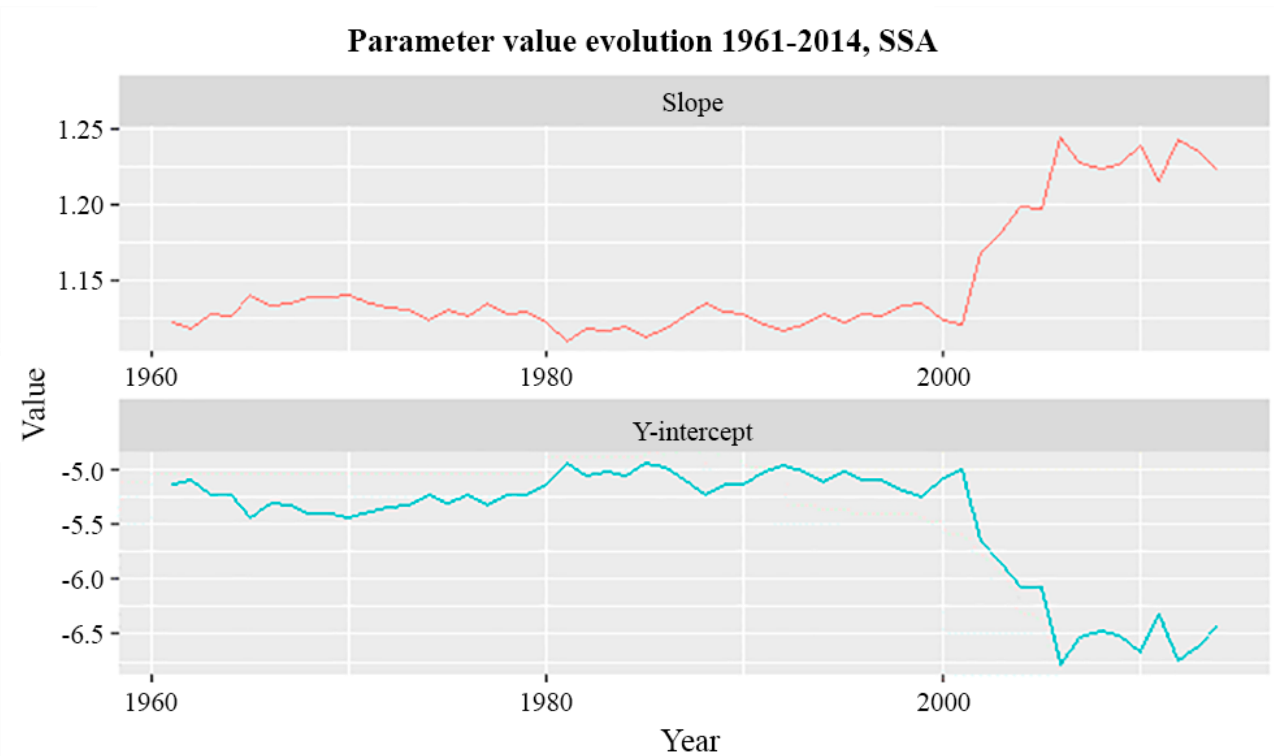

Figure 5. Evolution of the Sub-Saharan Africa (SSA) region slope and y-intercept values in Figure 2. Source: Authors' creation using FAO data (2015b; 2015c).

[1]We suspect this transition has more to do with a change in FAO imputation calibration than with real on-the-ground changes in livestock systems, but this is pure speculation. FAO could not be reached for comment on this matter.

Table 9. Milk production (MT) for 2010 disaggregated by production system (modelled).

Production system[1]	Kenya	Tanzania	Ethiopia	Uganda	Rwanda	Burundi
LGA	823,956	77,725	186,342	12,721	0	0
LGH	27,113	29,554	3,236	84,381	0	0
LGT	86,161	1,440	8,150	4,327	0	0
LGY	10	55	0	0	0	0
MIA	3,815	2,408	7,658	0	0	0
MIH	5,201	576	54	103	180	180
MIT	19,805	60	32,726	25	252	52
MRA	354,100	568,966	669,098	4,706	0	0
MRH	406,085	590,702	107,401	787,594	24,899	1,869
MRT	1,419,822	132,089	2,920,076	98,478	108,596	17,908
MRY	13	331	0	0	0	0
Other	139,083	112,794	100,590	244,653	9,957	10,177
Urban	41,246	48,712	22,668	3,186	2,445	232
Total	3,326,409	1,565,412	4,057,999	1,240,173	146,329	30,418
FAOstat total	3,638,592	1,649,857	4,057,998	1,377,000	162,302	30,418
% difference	9	5	0	10	10	0
MR Subtotal (*Q*)	2,180,007	1,291,758	3696575	890,778	133,495	19,776
α	1.277	1.250	1.225	1.258	1.277	1.250
β	-5.833	-6.259	-6.259	-6.137	-5.833	-5.933

[1]For meaning of acronyms, see Table 1.

Results

Ex-ante approaches offer a forward-looking view of potential return on investment in an agricultural technology. The previous sections illustrate how the economic surplus model of Alston et al. (1995) can be parameterized, even in relatively sparse data environments. With the model parameterized, we can now populate the outcome map based on aforementioned adoption and benefit criteria.

Plausible outcomes map

Below we present NPV estimates based on a wide range of potential production increases resulting from adoption of the new *Brachiaria* technology in Eastern Africa (Figures 6–8). For each potential production increase, we also present results over the range of all possible adoption rates (0–100% at 5% intervals). Outcomes are calculated in terms of producer, consumer and total surplus. Each map cell is colored in accordance with the NPV it contains. Lower values are redder, higher values are greener; and the 50th percentile of NPVs is colored yellow.

NPV outcomes isoquant map and envelope formula

Results are also presented in an isoquant format in Figure 9. Analogous to isobars on a weather map or elevation contours on a terrain map, each isoquant represents an NPV outcome level, and each point on an isoquant indicates the production increase and adoption rate necessary to reach that NPV outcome. Equations fitted to these isoquants are of the form:

$$A_{max} \approx \frac{\gamma_i}{E[y]} \qquad \text{Eq. 2}$$

for the i^{th} NPV isoquant, where A_{max} is the adoption rate, $E[y]$ is the expected increase in production resulting from adoption, and γ_i is a parameter to be fitted. This equation implies a one-to-one tradeoff between the adoption rate and the expected percentage increase in production. If the increase in production 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.

Plotting the γ_i values against the log of their associated NPV values in Figure 9 reveals an interesting linear relationship (Figure 10) that permits us to reduce all possible NPV isoquants to a single formula (Equation 3).

$$A_{max} \approx \frac{\text{NPV}^{0.744}}{e^{6.775}E[y]} \qquad \text{Eq.3}$$

This envelope formula encapsulates the model such that, for a given NPV outcome, the adoption rate (A_{max}) and expected change in production ($E[y]$) are allowed to vary, while the other parameters are held constant at their values in Table 2, encoded in the fitted parameters 0.744 and 6.775. Using this formula, the reader may determine the adoption rate necessary to achieve any given NPV outcome for any given percentage increase in production (or vice versa).

Adoption rate (%)	Increase in production (%)											
	5	10	15	20	25	30	35	40	45	50	55	60
5	-15,245	-11,731	-8,216	-4,698	-1,178	2,344	5,868	9,395	12,924	16,456	19,989	23,525
10	-11,731	-4,698	2,344	9,395	16,456	23,525	30,603	37,691	44,787	51,893	59,008	66,131
15	-8,216	2,344	12,924	23,525	34,146	44,787	55,449	66,131	76,834	87,557	98,300	109,063
20	-4,698	9,395	23,525	37,691	51,893	66,131	80,406	94,716	109,063	123,446	137,866	152,321
25	-1,178	16,456	34,146	51,893	69,696	87,557	105,473	123,446	141,476	159,563	177,706	195,905
30	2,344	23,525	44,787	66,131	87,557	109,063	130,652	152,321	174,073	195,905	217,819	239,815
35	5,868	30,603	55,449	80,406	105,473	130,652	155,941	181,341	206,852	232,474	258,207	284,050
40	9,395	37,691	66,131	94,716	123,446	152,321	181,341	210,506	239,815	269,269	298,868	328,612
45	12,924	44,787	76,834	109,063	141,476	174,073	206,852	239,815	272,961	306,290	339,803	373,499
50	16,456	51,893	87,557	123,446	159,563	195,905	232,474	269,269	306,290	343,538	381,012	418,712
55	19,989	59,008	98,300	137,866	177,706	217,819	258,207	298,868	339,803	381,012	422,495	464,251
60	23,525	66,131	109,063	152,321	195,905	239,815	284,050	328,612	373,499	418,712	464,251	510,116
65	27,063	73,264	119,847	166,813	214,161	261,892	310,005	358,500	407,378	456,639	506,281	556,306
70	30,603	80,406	130,652	181,341	232,474	284,050	336,070	388,534	441,441	494,791	548,585	602,823
75	34,146	87,557	141,476	195,905	250,843	306,290	362,247	418,712	475,687	533,170	591,163	649,665
80	37,691	94,716	152,321	210,506	269,269	328,612	388,534	449,035	510,116	571,776	634,015	696,833
85	41,238	101,885	163,187	225,142	287,751	351,015	414,932	479,503	544,728	610,607	677,140	744,327
90	44,787	109,063	174,073	239,815	306,290	373,499	441,441	510,116	579,524	649,665	720,540	792,147
95	48,339	116,250	184,979	254,524	324,886	396,065	468,061	540,873	614,503	688,949	764,213	840,293
100	51,893	123,446	195,905	269,269	343,538	418,712	494,791	571,776	649,665	728,460	808,160	888,765

Figure 6. Program level NPV outcomes map on a producer surplus basis for various adoption rates of *Brachiaria* technology and production responses in Sub-Saharan Africa. Values are in thousands of US dollars.

Adoption rate (%)	Increase in production (%)											
	5	10	15	20	25	30	35	40	45	50	55	60
5	-13,840	-8,922	-4,000	925	5,853	10,784	15,718	20,656	25,596	30,540	35,487	40,437
10	-8,922	925	10,784	20,656	30,540	40,437	50,347	60,269	70,204	80,152	90,113	100,086
15	-4,000	10,784	25,596	40,437	55,307	70,204	85,131	100,086	115,069	130,081	145,122	160,191
20	925	20,656	40,437	60,269	80,152	100,086	120,070	140,105	160,191	180,327	200,514	220,752
25	5,853	30,540	55,307	80,152	105,077	130,081	155,165	180,327	205,569	230,890	256,290	281,769
30	10,784	40,437	70,204	100,086	130,081	160,191	190,414	220,752	251,204	281,769	312,449	343,243
35	15,718	50,347	85,131	120,070	155,165	190,414	225,819	261,380	297,095	332,966	368,992	405,173
40	20,656	60,269	100,086	140,105	180,327	220,752	261,380	302,210	343,243	384,479	425,917	467,559
45	25,596	70,204	115,069	160,191	205,569	251,204	297,095	343,243	389,648	436,309	483,226	530,401
50	30,540	80,152	130,081	180,327	230,890	281,769	332,966	384,479	436,309	488,455	540,919	593,699
55	35,487	90,113	145,122	200,514	256,290	312,449	368,992	425,917	483,226	540,919	598,995	657,454
60	40,437	100,086	160,191	220,752	281,769	343,243	405,173	467,559	530,401	593,699	657,454	721,664
65	45,390	110,072	175,288	241,041	307,328	374,151	441,509	509,403	577,832	646,796	716,296	786,331
70	50,347	120,070	190,414	261,380	332,966	405,173	478,001	551,450	625,519	700,210	775,522	851,454
75	55,307	130,081	205,569	281,769	358,683	436,309	514,648	593,699	673,464	753,941	835,131	917,034
80	60,269	140,105	220,752	302,210	384,479	467,559	551,450	636,151	721,664	807,988	895,123	983,069
85	65,235	150,142	235,964	322,701	410,354	498,923	588,407	678,807	770,122	862,352	955,499	1,049,561
90	70,204	160,191	251,204	343,243	436,309	530,401	625,519	721,664	818,836	917,034	1,016,258	1,116,508
95	75,177	170,253	266,472	363,836	462,342	561,993	662,787	764,725	867,806	972,031	1,077,400	1,183,912
100	80,152	180,327	281,769	384,479	488,455	593,699	700,210	807,988	917,034	1,027,346	1,138,926	1,251,773

Figure 7. Program level NPV outcomes map on a consumer surplus basis for various adoption rates of *Brachiaria* technology and production responses in Sub-Saharan Africa. Values are in thousands of US dollars.

Adoption rate (%)	Increase in production (%) 5	10	15	20	25	30	35	40	45	50	55	60
5	-10,329	-1,898	6,539	14,982	23,430	31,883	40,342	48,806	57,276	65,751	74,232	82,718
10	-1,898	14,982	31,883	48,806	65,751	82,718	99,706	116,716	133,747	150,801	167,876	184,973
15	6,539	31,883	57,276	82,718	108,208	133,747	159,336	184,973	210,659	236,393	262,177	288,010
20	14,982	48,806	82,718	116,716	150,801	184,973	219,231	253,577	288,010	322,529	357,136	391,829
25	23,430	65,751	108,208	150,801	193,529	236,393	279,393	322,529	365,801	409,208	452,751	496,430
30	31,883	82,718	133,747	184,973	236,393	288,010	339,822	391,829	444,032	496,430	549,024	601,813
35	40,342	99,706	159,336	219,231	279,393	339,822	400,516	461,476	522,703	584,195	645,954	707,979
40	48,806	116,716	184,973	253,577	322,529	391,829	461,476	531,471	601,813	672,503	743,541	814,926
45	57,276	133,747	210,659	288,010	365,801	444,032	522,703	601,813	681,364	761,355	841,785	922,655
50	65,751	150,801	236,393	322,529	409,208	496,430	584,195	672,503	761,355	850,749	940,686	1,031,167
55	74,232	167,876	262,177	357,136	452,751	549,024	645,954	743,541	841,785	940,686	1,040,245	1,140,460
60	82,718	184,973	288,010	391,829	496,430	601,813	707,979	814,926	922,655	1,031,167	1,140,460	1,250,536
65	91,209	202,091	313,891	426,609	540,245	654,798	770,270	886,659	1,003,966	1,122,190	1,241,333	1,361,393
70	99,706	219,231	339,822	461,476	584,195	707,979	832,827	958,739	1,085,716	1,213,757	1,342,863	1,473,033
75	108,208	236,393	365,801	496,430	628,281	761,355	895,650	1,031,167	1,167,906	1,305,867	1,445,050	1,585,454
80	116,716	253,577	391,829	531,471	672,503	814,926	958,739	1,103,942	1,250,536	1,398,519	1,547,894	1,698,658
85	125,229	270,783	417,906	566,599	716,861	868,693	1,022,094	1,177,065	1,333,605	1,491,715	1,651,395	1,812,644
90	133,747	288,010	444,032	601,813	761,355	922,655	1,085,716	1,250,536	1,417,115	1,585,454	1,755,553	1,927,411
95	142,271	305,259	470,207	637,115	805,984	976,813	1,149,603	1,324,354	1,501,065	1,679,736	1,860,368	2,042,961
100	150,801	322,529	496,430	672,503	850,749	1,031,167	1,213,757	1,398,519	1,585,454	1,774,561	1,965,841	2,159,293

Figure 8. Program level NPV outcomes map on a total surplus basis for various adoption rates of *Brachiaria* technology and production responses in Sub-Saharan Africa. Values are in thousands of US dollars.

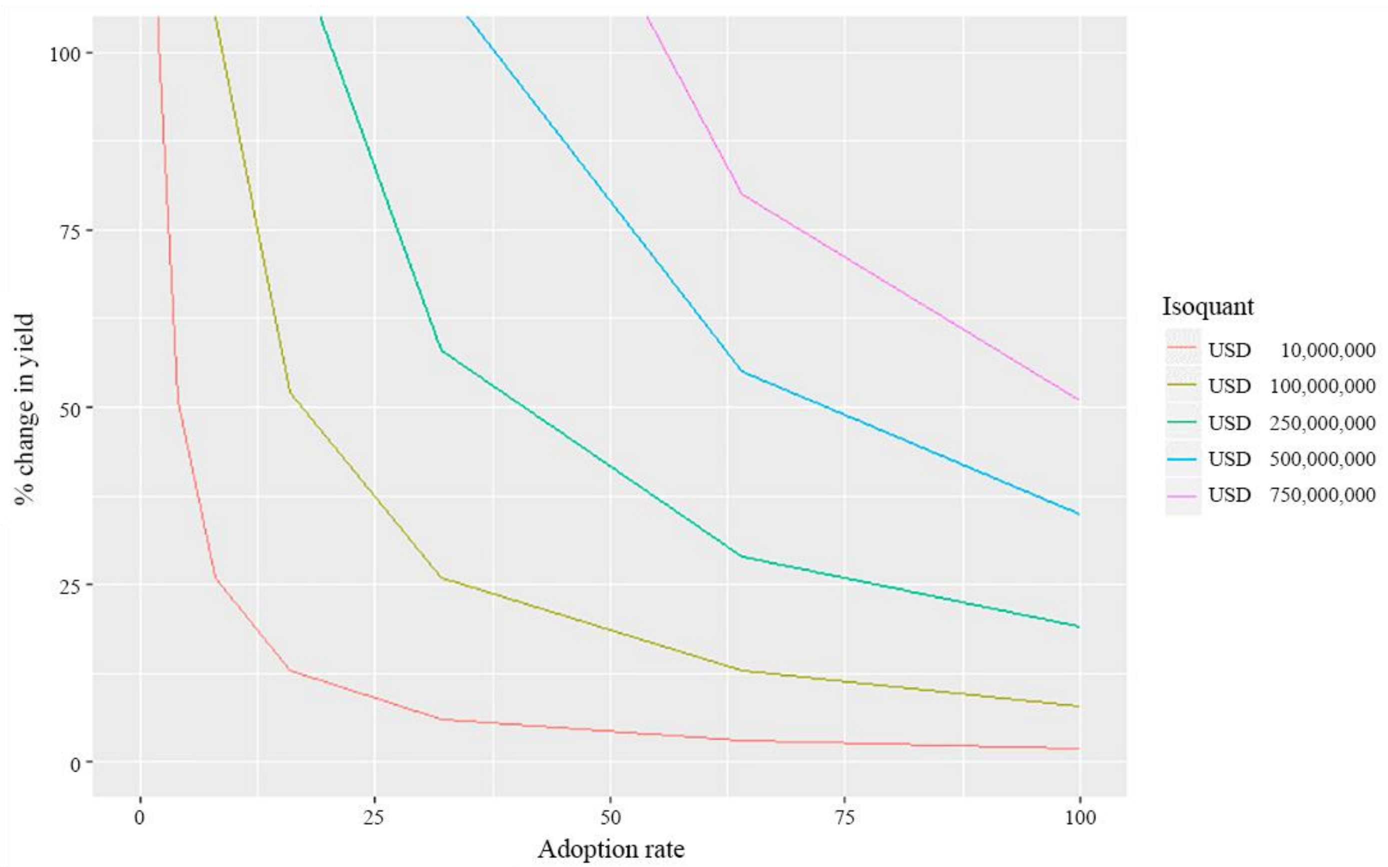

Figure 9. NPV isoquants for a range of potential combinations of adoption rate ceilings and changes (%) in fresh milk production resulting from adoption of improved *Brachiaria* technology**.**

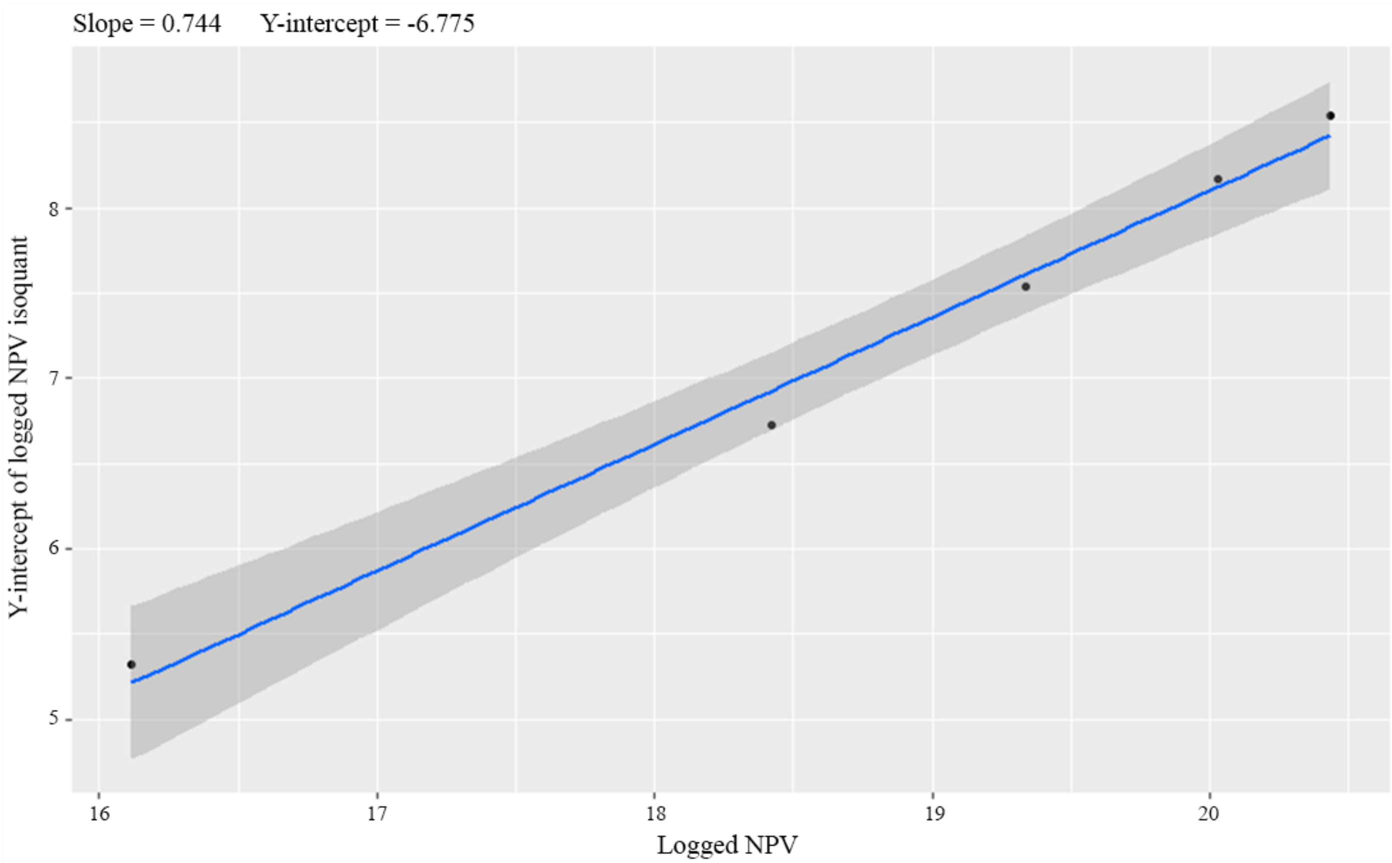

Figure 10. The γ_i from the isoquants in Figure 7 plotted against the log of their corresponding NPV.

Sensitivity analyses

In any model, results may be sensitive to inaccuracies in input parameter values. It is therefore important to assess how sensitive the results presented above are to inaccuracies in key parameters, especially those parameters which are most uncertain. Sensitivity to fresh cow milk supply and demand elasticity values in particular warrant close scrutiny, as these were defined for all of Sub-Saharan Africa. In Figure 11, we present sensitivity analyses on these plus 2 other parameters.

In these sensitivity maps, an absolute value of 1 means that the NPV outcome for that scenario is as accurate as the parameter value. In other words, if the parameter value is off by 10%, then the NPV will also be off by 10%. Figures 11a and 11d indicate this kind of 1:1 model sensitivity to inaccuracy in the supply elasticity and producer price/quantity affected parameters for most scenarios, with sensitivity becoming extreme for a few of the low adoption scenarios on the fringe of the plausible outcomes space. Figure 11C indicates more moderate sensitivity to inaccuracy in the change in input cost parameter, and Figure 11B indicates very little sensitivity to inaccuracy in the demand elasticity.

Broadly speaking, the modelled NPV outcomes are about as accurate as the parameter values for supply elasticity, producer prices or quantity affected. The model is also moderately sensitive to inaccuracy in the change in input costs parameter. However, for a wide range of plausible scenarios, even a substantial inaccuracy in any single one of these would 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.

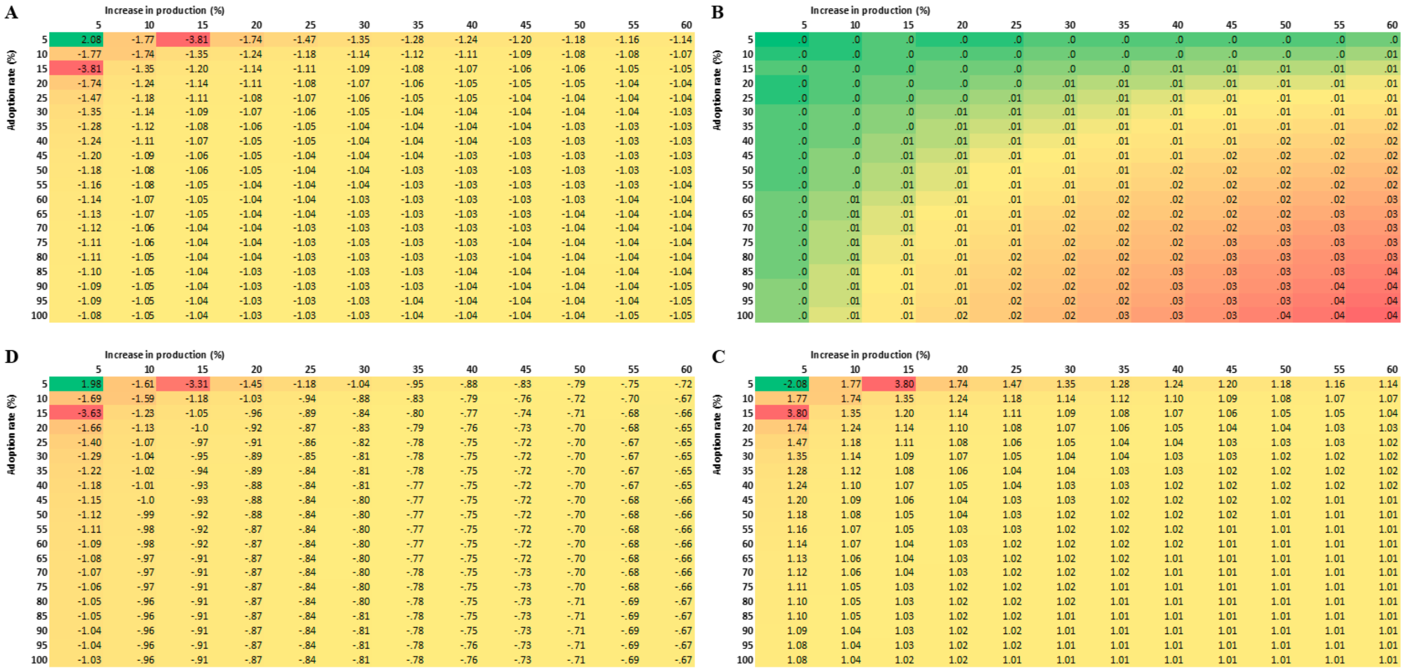

Figure 11. Sensitivity maps for (clockwise from top left): **A)** the supply elasticity; **B)** the demand elasticity; **C)** the producer price/quantity affected; and **D)** the expected change in cost. Sensitivity is here defined as the elasticity of the modelled NPV (on a total surplus basis) with respect to the given parameter.

Discussion and Conclusions

The results of this economic surplus analysis suggest that investment in a research program involving the development of improved forage varieties for release in Eastern Africa would be a low-risk, high-reward endeavor. Preliminary data from ongoing multi-site trials in Kenya and Rwanda suggest that release and uptake of improved forages would increase milk production by 15–40%. On a producer surplus basis alone, NPV outcomes are positive across this entire range so long as the adoption rate is at least 10%, and rise quickly into the tens of millions of dollars for a wide range of plausible adoption rates. When consumer side benefits are added in, the NPV outcomes are much greater still, reaching half a billion dollars for a wide range of plausible scenarios.

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 the baseline milk production), and because we assume there is no increase in input costs associated with adoption of the new technology. The relatively brief research period, compared with prior CIAT forage research programs, also contributes to this result.

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 fixed capital improvements and other transition costs that might be associated with adoption of the new technology, e.g. terrain preparation, fencing, etc. The model employed in this study also makes no allowance for the often complex nature of land tenure in Eastern Africa, and the many ways this and other heterogeneous farm characteristics can vary across landscapes in the study zone. In other words, the model assumes that the percentage increase in production is the same for all adopting farms, regardless of variation in local conditions and factor endowments. Finally, we do not account for potential delays in diffusion due, for example, to production of planting materials by private sector actors subsequent to release of the research product. 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 from associating the grass with a forage legume, the storage and/or sale of hay, the spread of climate-adapted push-pull systems, and potential multiplier effects on the broader economy.

The model results are presented in a heat map format that covers a broad range of potential outcomes, allowing the reader to compensate for the aforementioned potential biases by choosing an adoption rate consistent with his/her own level of optimism/pessimism regarding these sources of uncertainty, and with his/her interpretation of the regional expert opinions in Tables 5 and 6. The model envelope equation is also presented (Equation 1), whereby readers can calculate, for any given production increase that seems feasible to them, the modelled adoption rate required for a desired level of NPV (on a total surplus basis). This reporting format is intended to invite exploratory 'what-if' questions and inter-comparison of scenarios which can be further refined with new data as they become available.

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(Note of the editors: All hyperlinks were verified 22 September 2018.)

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