ISSN: 2346-3775

Tropical Grasslands -Forrajes Tropicales

Online Journal

Vol. 6 No. 3

June – September 2018

Published by:
International Center for Tropical Agriculture (CIAT), Cali, Colombia
In cooperation with:
Chinese Academy of Tropical Agricultural Sciences (CATAS)

www.tropicalgrasslands.info

Principal Contacts

Rainer Schultze-Kraft
International Center for Tropical Agriculture (CIAT)
Colombia
Phone: +57 2 4450100 Ext. 3036
Email: CIAT-TGFT-Journal@cgiar.org

Technical Support
José Luis Urrea Benítez
International Center for Tropical Agriculture (CIAT)
Colombia
Phone: +57 2 4450100 Ext. 3354
Email: CIAT-TGFT-Journal@cgiar.org

Table of Contents

Research Papers

Tropical Grasslands-Forrajes Tropicales (2018) Vol. 6(3):117–133
DOI: 10.17138/TGFT(6)117-133

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*

BEN SCHIEK[1], CARLOS GONZÁLEZ[1], SOLOMON MWENDIA[2] AND STEVEN D. PRAGER[1]

[1]*Decision and Policy Analysis Area, International Center for Tropical Agriculture (CIAT), Cali, Colombia*. ciat.cgiar.org
[2]*Agrobiodiversity Research Area, International Center for Tropical Agriculture (CIAT), Nairobi, Kenya.* ciat.cgiar.org

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.

Correspondence: Ben Schiek, International Center for Tropical Agriculture (CIAT), Apartado Aéreo 6713, Cali, Colombia.
Email: b.schiek@cgiar.org

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).

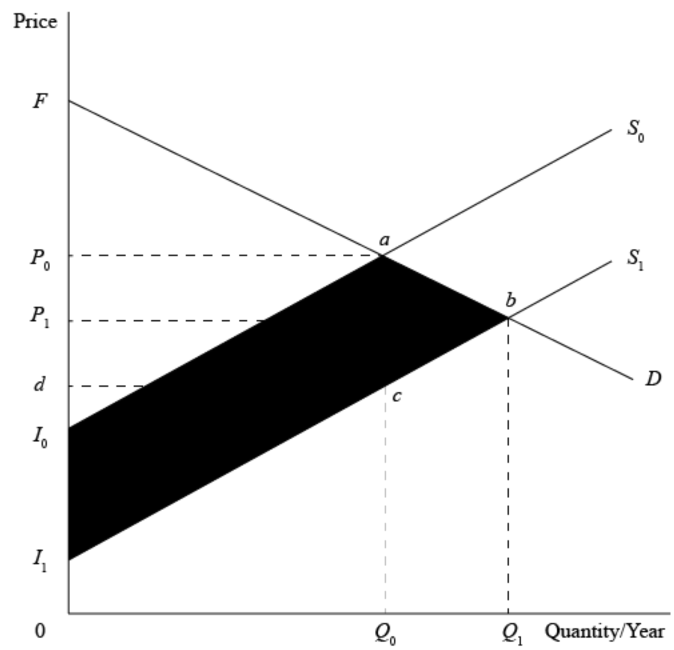

Figure 1. Conceptual representation of the economic surplus model for closed economies (Alston et al. 1995). For a given year in a given market, uptake of the new technology results in higher production and hence a supply curve shift from S_0 to S_1, giving the increase in total surplus I_0abI_1.

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.

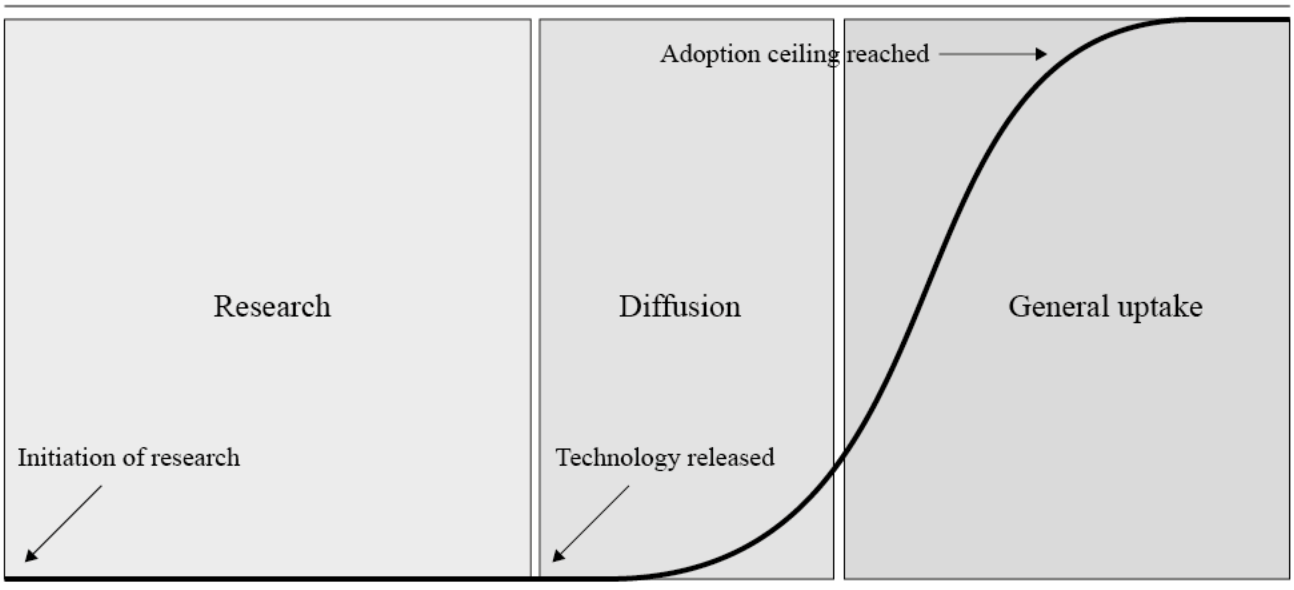

Figure 2. Conceptual illustration of the logistic technology adoption curve.

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

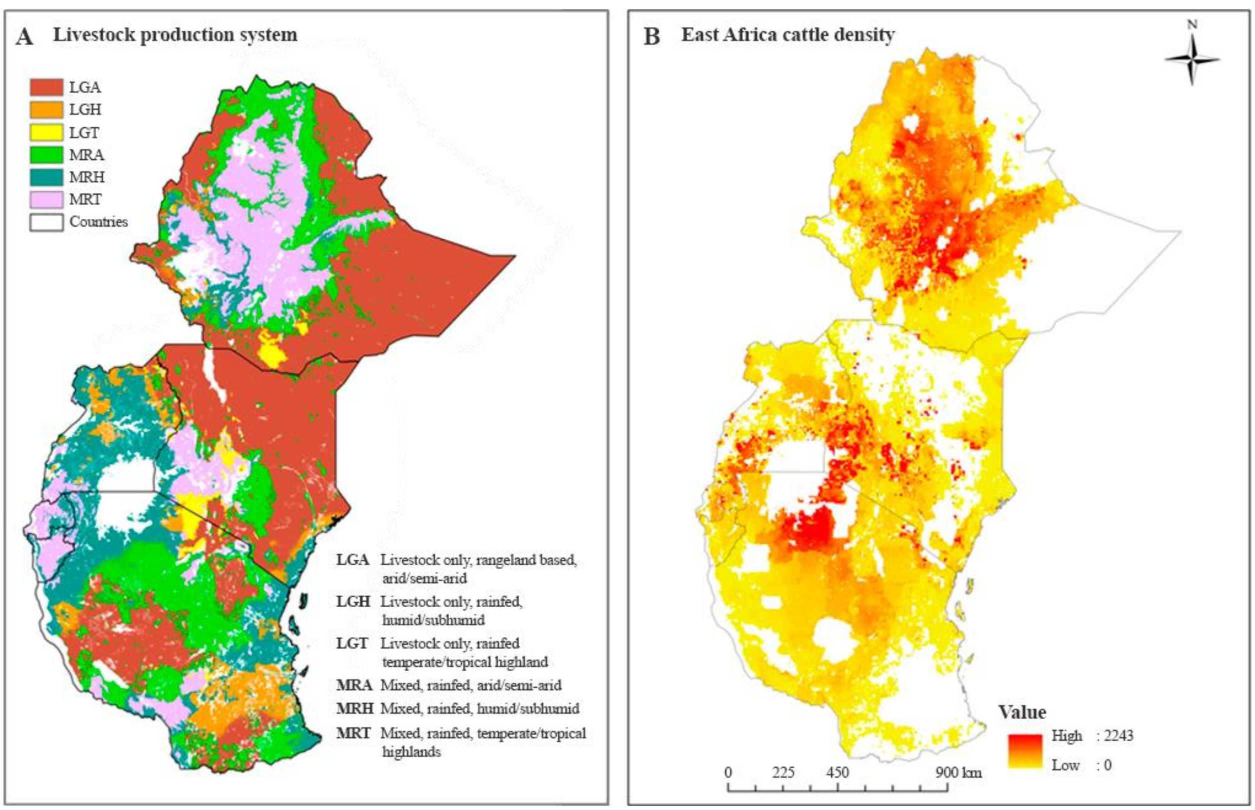

Figure 3. A) Production systems map of the study area. Source: Authors' creation using the production systems map data v 5.0 (FAO and ILRI 2011); **B)** Cattle density map of the study area. Source: Authors' creation using the Gridded Livestock of the World map data v 2.01 (FAO 2010).

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.

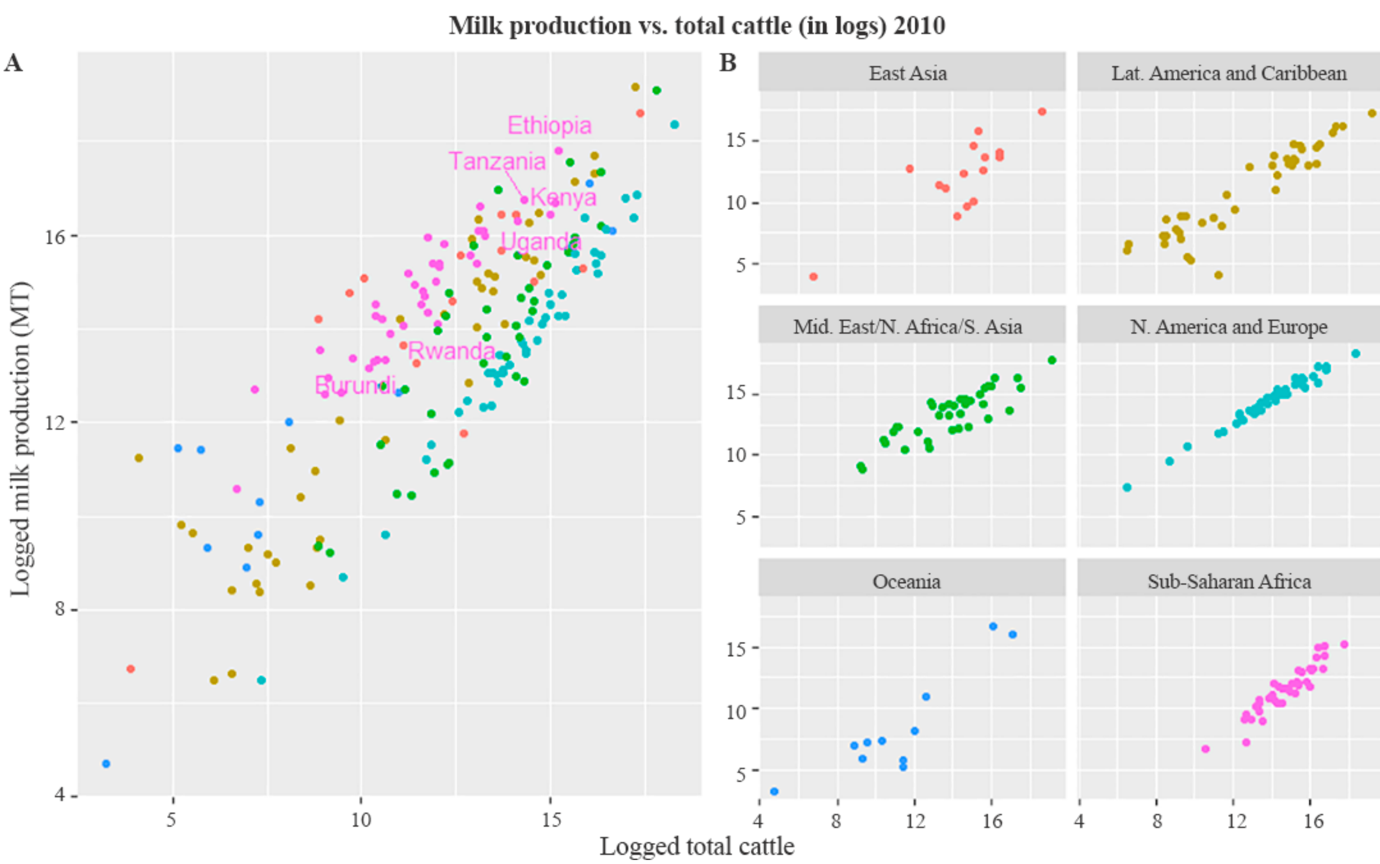

Figure 4. 2010 Milk production plotted against total cattle in logs: **A)** for all countries in the world; and **B)** in separate plots by region. Source: Authors' creation using FAO data (2015b; 2015c)**.**

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.

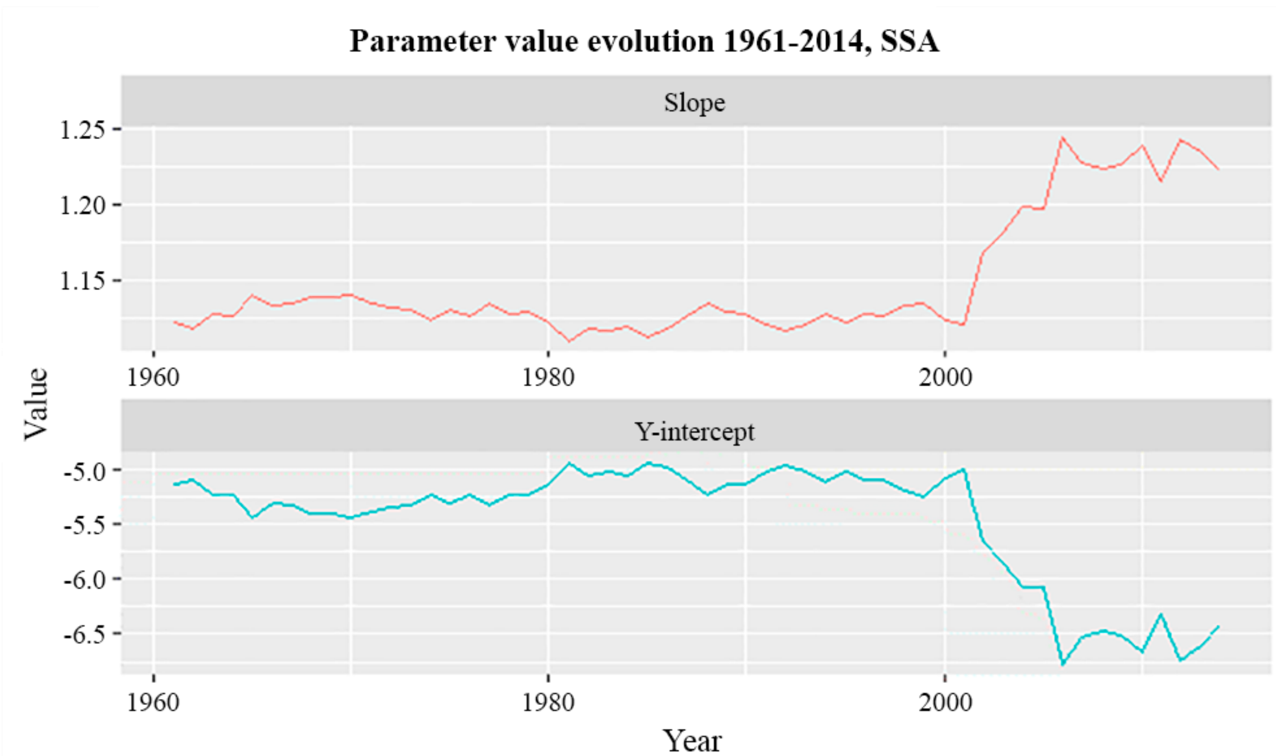

Figure 5. Evolution of the Sub-Saharan Africa (SSA) region slope and y-intercept values in Figure 2. Source: Authors' creation using FAO data (2015b; 2015c).

[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:

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

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).

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

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).

	Increase in production (%)											
Adoption rate (%)	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.

	Increase in production (%)											
Adoption rate (%)	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.

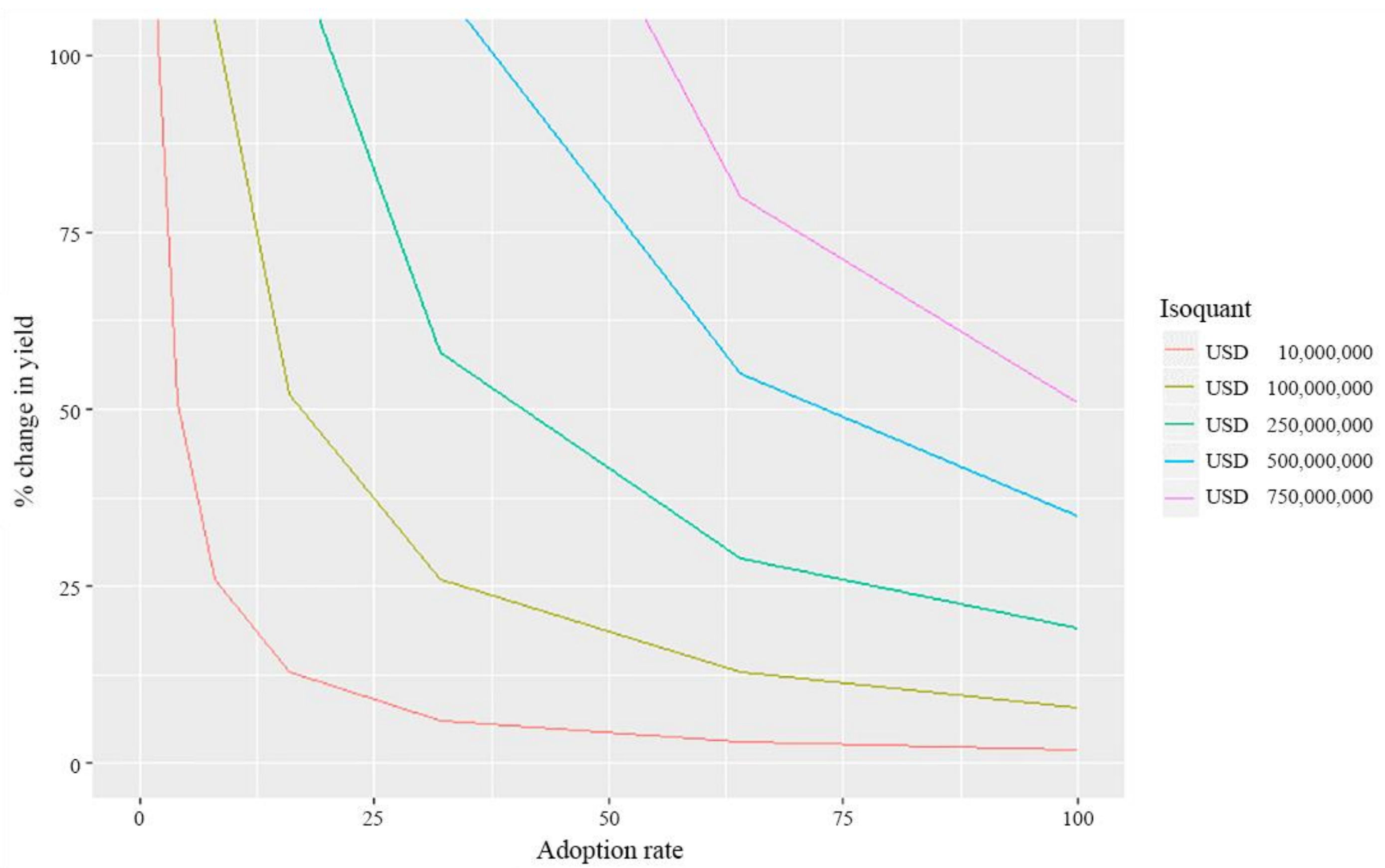

Figure 9. NPV isoquants for a range of potential combinations of adoption rate ceilings and changes (%) in fresh milk production resulting from adoption of improved *Brachiaria* technology**.**

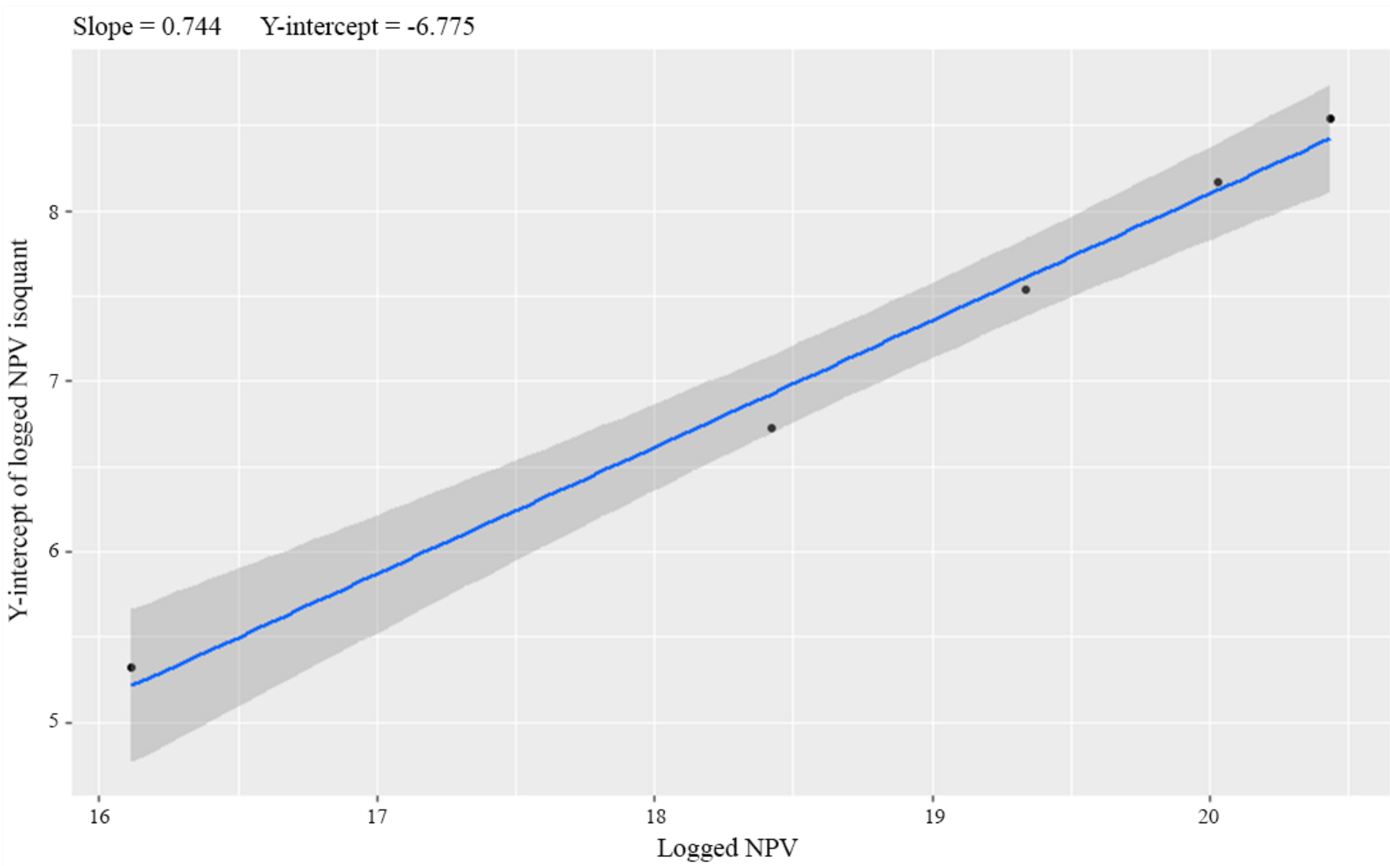

Figure 10. The γ_i from the isoquants in Figure 7 plotted against the log of their corresponding NPV.

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.

A

Adoption rate (%) \ Increase in production (%)	5	10	15	20	25	30	35	40	45	50	55	60
5	2.08	-1.77	-3.81	-1.74	-1.47	-1.35	-1.28	-1.24	-1.20	-1.18	-1.16	-1.14
10	-1.77	-1.74	-1.35	-1.24	-1.18	-1.14	-1.12	-1.11	-1.09	-1.08	-1.08	-1.07
15	-3.81	-1.35	-1.20	-1.14	-1.11	-1.09	-1.08	-1.07	-1.06	-1.06	-1.05	-1.05
20	-1.74	-1.24	-1.14	-1.11	-1.08	-1.07	-1.06	-1.05	-1.05	-1.05	-1.04	-1.04
25	-1.47	-1.18	-1.11	-1.08	-1.07	-1.06	-1.05	-1.05	-1.04	-1.04	-1.04	-1.04
30	-1.35	-1.14	-1.09	-1.07	-1.06	-1.05	-1.04	-1.04	-1.04	-1.04	-1.04	-1.03
35	-1.28	-1.12	-1.08	-1.06	-1.05	-1.04	-1.04	-1.04	-1.04	-1.03	-1.03	-1.03
40	-1.24	-1.11	-1.07	-1.05	-1.05	-1.04	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03
45	-1.20	-1.09	-1.06	-1.05	-1.04	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.03
50	-1.18	-1.08	-1.06	-1.05	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.03	-1.03
55	-1.16	-1.08	-1.05	-1.04	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.03	-1.04
60	-1.14	-1.07	-1.05	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04
65	-1.13	-1.07	-1.05	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04
70	-1.12	-1.06	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04
75	-1.11	-1.06	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04
80	-1.11	-1.05	-1.04	-1.04	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04
85	-1.10	-1.05	-1.04	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04	-1.04
90	-1.09	-1.05	-1.04	-1.03	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04	-1.05
95	-1.09	-1.05	-1.04	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04	-1.04	-1.05
100	-1.08	-1.05	-1.04	-1.03	-1.03	-1.03	-1.04	-1.04	-1.04	-1.04	-1.05	-1.05

B

Adoption rate (%) \ Increase in production (%)	5	10	15	20	25	30	35	40	45	50	55	60
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	.02	.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	.03	.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

D

Adoption rate (%) \ Increase in production (%)	5	10	15	20	25	30	35	40	45	50	55	60
5	1.98	-1.61	-3.31	-1.45	-1.18	-1.04	-.95	-.88	-.83	-.79	-.75	-.72
10	-1.69	-1.59	-1.18	-1.03	-.94	-.88	-.83	-.79	-.76	-.72	-.70	-.67
15	-3.63	-1.23	-1.05	-.96	-.89	-.84	-.80	-.77	-.74	-.71	-.68	-.66
20	-1.66	-1.13	-1.0	-.92	-.87	-.83	-.79	-.76	-.73	-.70	-.68	-.65
25	-1.40	-1.07	-.97	-.91	-.86	-.82	-.78	-.75	-.72	-.70	-.67	-.65
30	-1.29	-1.04	-.95	-.89	-.85	-.81	-.78	-.75	-.72	-.70	-.67	-.65
35	-1.22	-1.02	-.94	-.89	-.84	-.81	-.78	-.75	-.72	-.70	-.67	-.65
40	-1.18	-1.01	-.93	-.88	-.84	-.81	-.77	-.75	-.72	-.70	-.67	-.65
45	-1.15	-1.0	-.93	-.88	-.84	-.80	-.77	-.75	-.72	-.70	-.68	-.66
50	-1.12	-.99	-.92	-.88	-.84	-.80	-.77	-.75	-.72	-.70	-.68	-.66
55	-1.11	-.98	-.92	-.87	-.84	-.80	-.77	-.75	-.72	-.70	-.68	-.66
60	-1.09	-.98	-.92	-.87	-.84	-.80	-.77	-.75	-.72	-.70	-.68	-.66
65	-1.08	-.97	-.91	-.87	-.84	-.80	-.77	-.75	-.72	-.70	-.68	-.66
70	-1.07	-.97	-.91	-.87	-.84	-.80	-.78	-.75	-.73	-.70	-.68	-.66
75	-1.06	-.97	-.91	-.87	-.84	-.80	-.78	-.75	-.73	-.70	-.68	-.66
80	-1.05	-.96	-.91	-.87	-.84	-.80	-.78	-.75	-.73	-.71	-.69	-.67
85	-1.05	-.96	-.91	-.87	-.84	-.81	-.78	-.75	-.73	-.71	-.69	-.67
90	-1.04	-.96	-.91	-.87	-.84	-.81	-.78	-.75	-.73	-.71	-.69	-.67
95	-1.04	-.96	-.91	-.87	-.84	-.81	-.78	-.76	-.73	-.71	-.69	-.67
100	-1.03	-.96	-.91	-.87	-.84	-.81	-.78	-.76	-.73	-.71	-.69	-.67

C

Adoption rate (%) \ Increase in production (%)	5	10	15	20	25	30	35	40	45	50	55	60
5	-2.08	1.77	3.80	1.74	1.47	1.35	1.28	1.24	1.20	1.18	1.16	1.14
10	1.77	1.74	1.35	1.24	1.18	1.14	1.12	1.10	1.09	1.08	1.07	1.07
15	3.80	1.35	1.20	1.14	1.11	1.09	1.08	1.07	1.06	1.05	1.05	1.04
20	1.74	1.24	1.14	1.10	1.08	1.07	1.06	1.05	1.04	1.04	1.03	1.03
25	1.47	1.18	1.11	1.08	1.06	1.05	1.04	1.04	1.03	1.03	1.03	1.02
30	1.35	1.14	1.09	1.07	1.05	1.04	1.04	1.03	1.03	1.02	1.02	1.02
35	1.28	1.12	1.08	1.06	1.04	1.04	1.03	1.03	1.02	1.02	1.02	1.02
40	1.24	1.10	1.07	1.05	1.04	1.03	1.03	1.02	1.02	1.02	1.02	1.02
45	1.20	1.09	1.06	1.04	1.03	1.03	1.02	1.02	1.02	1.02	1.01	1.01
50	1.18	1.08	1.05	1.04	1.03	1.02	1.02	1.02	1.02	1.01	1.01	1.01
55	1.16	1.07	1.05	1.03	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01
60	1.14	1.07	1.04	1.03	1.02	1.02	1.02	1.02	1.01	1.01	1.01	1.01
65	1.13	1.06	1.04	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01
70	1.12	1.06	1.04	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01
75	1.11	1.05	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01
80	1.10	1.05	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01
85	1.10	1.05	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01
90	1.09	1.04	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01
95	1.08	1.04	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01
100	1.08	1.04	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01

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.

Acknowledgments

This work was funded by the CIAT strategic fund and the Global Futures and Strategic Foresight activity of the Policy, Institutions, and Markets research program of the CGIAR, with contributions from the CGIAR Research Program on Livestock. We thank the CIAT Tropical Forages teams in both Colombia and Kenya for their deep insights into forage issues in LAC and East Africa.

References

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

Alston JM; Norton GW; Pardey PG. 1995. Science under scarcity: Principles and practice for agricultural research evaluation and priority setting. Cornell University Press, Ithaca, NY, USA. goo.gl/RQfUFY

Antle JM; Jones JW; Rosenzweig CE. 2017. Next generation agricultural system data, models and knowledge products: Introduction. Agricultural Systems 155:186–190. DOI: 10.1016/j.agsy.2016.09.003

CSB (Climate-Smart *Brachiaria* Program). 2016. CSB annual review meeting. KALRO (Kenya Agricultural and Livestock Research Organization), Embu, Kenya. goo.gl/VbzJ4D

Djikeng A; Rao IM; Njarui D; Mutimura M; Caradus J; Ghimire SR; Johnson L; Cardoso JA; Ahonsi M; Kelemu S. 2014. Climate-smart *Brachiaria* grasses for improving livestock production in East Africa. Tropical Grasslands-Forrajes Tropicales 2:38–39. DOI: 10.17138/tgft(2)38-39

Dzowela BH. 1990. PANESA (The Pastures Network for Eastern and Southern Africa): Its regional collaborative research programme. Tropical Grasslands 24:113–120. goo.gl/xJqBM7

Elbasha E; Thornton PK; Tarawali G. 1999. An ex post economic impact assessment of planted forages in West Africa. ILRI Impact Assessment Series, no. 2. ILRI (International Livestock Research Institute), Nairobi, Kenya. hdl.handle.net/10568/502

FAO (Food and Agriculture Organization of the United Nations). 2009. The State of Food and Agriculture: Livestock in the balance. FAO, Rome, Italy. goo.gl/BRf8FH

FAO (Food and Agriculture Organization of the United Nations). 2010. Cattle distribution - Gridded Livestock of the World v 2.01. FAO, Rome, Italy. goo.gl/RGgPXo

FAO (Food and Agriculture Organization of the United Nations). 2015a. FAOSTAT Statistical Database Producer Prices. FAO, Rome, Italy. goo.gl/5dYgqN

FAO (Food and Agriculture Organization of the United Nations). 2015b. FAOSTAT Statistical Database Live Animals. FAO, Rome, Italy. goo.gl/8yXBgN

FAO (Food and Agriculture Organization of the United Nations). 2015c. FAOSTAT Statistical Database Livestock Primary. FAO, Rome, Italy. goo.gl/a4RbnP

FAO (Food and Agriculture Organization of the United Nations); ILRI (International Livestock Research Institute). 2011. Global Livestock Production Systems v 5.0. FAO, Rome, Italy. goo.gl/57FSXx

Fisher MJ; Rao IM; Ayarza MA; Lascano CE; Sanz JI; Thomas RJ; Vera RR. 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371:236–238. DOI: 10.1038/371236a0

Fisher MJ; Kerridge PC. 1996. The agronomy and physiology of *Brachiaria* species. In: Miles JW; Maass BL; Valle CB do; Kumble V, eds. *Brachiaria*: Biology, agronomy, and improvement. CIAT (Centro Internacional de Agricultura Tropical); EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), Cali, Colombia. p. 43–52. hdl.handle.net/10568/54880

Ghimire SR; Njarui D; Mutimura M; Cardoso JA; Johnson L; Gichangi E; Teasdale S; Odokonyero K; Caradus JR; Rao IM; Djikeng A. 2015. Climate-smart *Brachiaria* for improving livestock production in East Africa: Emerging opportunities. In: Vijay D; Srivastava MK; Gupta CK; Malaviya DR; Roy MM; Mahanta SK; Singh JB; Maity A; and Ghosh PK, eds. Proceedings of the XXIII International Grassland Congress, New Delhi, India, 20–24 November 2015. p. 361–370. hdl.handle.net/10568/69364

González C; Schiek B; Mwendia S; Prager S. 2016. 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. CIAT (Centro Internacional de Agricultura Tropical), Cali, Colombia. hdl.handle.net/10568/77557

Jank L; Barrios SC; Valle CB do; Simeão RM; Alves GF. 2014. The value of improved pastures to Brazilian beef production. Crop & Pasture Science 65:1132–1137. DOI: 10.1071/cp13319

Kabirizi J; Ziiwa E; Mugerwa S; Ndikumana J; Nanyennya W. 2013. Dry season forages for improving dairy production in smallholder systems in Uganda. Tropical Grasslands-Forrajes Tropicales 1:212–214. DOI: 10.17138/tgft(1)212-214

Maass BL; Midega CAO; Mutimura M; Rahetlah VB; Salgado P; Kabirizi JM; Khan ZR; Ghimire SR; Rao IM. 2015. Homecoming of *Brachiaria*: Improved hybrids prove useful for African animal agriculture. East African Agricultural and Forestry Journal 81:71–78. DOI: 10.1080/00128325.2015.1041263

Midega CAO; Bruce TJA; Pickett JA; Pittchar JO; Murage A; Khan ZR. 2015. Climate-adapted companion cropping increases agricultural productivity in East Africa. Field Crops Research 180:118–125. DOI: 10.1016/j.fcr.2015.05.022

Rakotoarisoa MA; Iafrate M; Paschali M. 2011. Why has Africa become a net food importer? Explaining Africa agricultural and food trade deficits. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. goo.gl/KDPsNT

Rao IM. 2014. Advances in improving adaptation of common bean and *Brachiaria* forage grasses to abiotic stress in the tropics. In: Pessarakli M, ed. Handbook of plant and crop physiology. CRC Press, Boca Raton, FL, USA. p. 847–889. hdl.handle.net/10568/35000

Rao IM; Kerridge PC; Macedo MCM. 1996. Nutritional requirements of *Brachiaria* and adaptation to acid soils. In: Miles JW; Maass BL; Valle CB do; Kumble V, eds. *Brachiaria*: Biology, agronomy, and improvement. CIAT (Centro Internacional de Agricultura Tropical); EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), Cali, Colombia. p. 53–71. hdl.handle.net/10568/82025

Robinson T; Pozzi F. 2011. Mapping supply and demand for animal-source foods to 2030. FAO Animal Production and Health Working Paper No. 2. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. goo.gl/yF5wE9

Robinson T; Thornton P; Franceschini G; Kruska R; Chiozza F; Notenbaert A; Cecchi G; Herrero M; Epprecht M; Fritz S; You L; Conchedda G; See L. 2011. Global livestock production systems. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. goo.gl/4vdz2C

Subbarao GV; Nakahara K; Hurtado MP; Ono H; Moreta DE; Salcedo AF; Yoshihashi AT; Ishikawa T; Ishitani M; Ohnishi-Kameyama M; Yoshida M; Rondon M; Rao IM; Lascano CE; Berry WL; Ito O. 2009. Evidence for biological nitrification inhibition in *Brachiaria* pastures. Proceedings of the National Academy of Sciences of the United States of America 106:17302–17307. DOI: 10.1073/pnas.0903694106

Thornton PK. 2010. Livestock production: Recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2853–2867. DOI: 10.1098/rstb.2010.0134

Thornton PK; Herrero M; Freeman HA; Okeyo AM; Rege E; Jones PG; McDermott JJ. 2007. Vulnerability, climate change and livestock – research opportunities and challenges for poverty alleviation. Journal of Semi-Arid Tropical Agricultural Research 4:1–23. hdl.handle.net/10568/2205

(Received for publication 14 November 2017; accepted 13 June 2018; published 30 September 2018)

DOI: 10.17138/TGFT(6)134-147

Research Paper

Variability for salt tolerance in a collection of *Panicum coloratum* var. *makarikariense* during early growth stages

Variabilidad en tolerancia a la salinidad en una colección de Panicum coloratum *var.* makarikariense *durante las etapas tempranas de crecimiento*

LUISINA CARDAMONE[1], ALEJANDRA CUATRÍN[2], KARINA GRUNBERG[3] AND MARÍA A. TOMÁS[2]

[1]*Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina.* www.conicet.gov.ar
[2]*Instituto de Tecnología Agropecuaria, (INTA), EEA Rafaela, Santa Fe, Argentina.* inta.gob.ar/rafaela
[3]*Centro de Investigación Agropecuaria (CIAP), INTA, Córdoba, Argentina.* inta.gob.ar/ciap

Abstract

Our aim was to investigate variability for salt tolerance in a collection of *Panicum coloratum* var. *makarikariense* of INTA EEA Rafaela, Argentina. *Panicum coloratum* is a C_4 perennial grass to be potentially used to increase forage production in areas affected by abiotic factors which reduce their productivity. We evaluated the response of half-sib families from different accessions to increasing salt concentrations under growth chamber conditions. Germination percentage (GP), GP (% of control) and index of germination decreased with increasing salinity, while mean germination time increased (P<0.001). After being exposed to saline conditions ungerminated seeds were able to recover in distilled water and many germinated. Salt tolerance was more variable between families within accessions than between accessions in all evaluated variables. At the seedling stage, morphological and physiological variables allowed differentiation among families on the basis of salt tolerance. Molecular characterization by ISSR molecular markers demonstrated variability within parent material and grouped families by accessions. A positive but low correlation between morphological and molecular distances was detected (r = 0.24; P = 0.032). Nonetheless, even after selection, enough molecular variability remained within tolerant families grouped by principal components analysis. In summary, materials of *P. coloratum* var. *makarikariense* from INTA EEA Rafaela showed both morphological and genetic variability for salinity tolerance and the contrasting genotypes could be used as parent materials to conduct breeding studies to improve salt tolerance in this species.

Keywords: Forage grass, germination, molecular markers, salinity, seedling growth.

Resumen

El objetivo del trabajo fue determinar la variabilidad en tolerancia a la salinidad en una colección *de Panicum coloratum* var. *makarikariense* existente en la estación experimental (EEA) Rafaela, INTA, Argentina. *Panicum coloratum* es una gramínea perenne tipo C_4 con potencial para incrementar la productividad ganadera en zonas afectadas por factores abióticos. En el estudio se evaluó la respuesta de familias de medios hermanos de diferentes accesiones de *P. coloratum* al incremento de la concentración salina. El porcentaje de germinación, la germinación con respecto al tratamiento control y el índice de germinación, disminuyeron con el incremento de la salinidad mientras el tiempo medio de germinación se incrementó (P<0.001). Las semillas sobrevivieron en agua destilada luego de ser expuestas a condiciones salinas. En salinidad, la variabilidad entre las familias dentro de las accesiones fue mayor que entre las accesiones, en

Correspondence: María Andrea Tomás, Instituto Nacional de Tecnología Agropecuaria, INTA EEA Rafaela, 2300 Rafaela, Santa Fe, Argentina.
E-mail: tomas.maria@inta.gob.ar

todas las variables evaluadas. En estado de plántula, las variables morfológicas y fisiológicas mostraron diferencias entre las familias por tolerancia a la salinidad. La caracterización molecular mediante marcadores moleculares ISSR demostró la existencia de variabilidad en el material parental y agrupó las familias por accesiones. Entre las distancias morfológicas y moleculares se detectó una correlación positiva pero baja (r = 0.24; P = 0.032). No obstante, aún después de la selección, las familias agrupadas como tolerantes por el análisis de componentes principales mantuvieron suficiente grado de variabilidad. En conclusión, el material de *P. coloratum* var. *makarikariense* del INTA EEA Rafaela mostró variabilidad tanto morfológica como genética en tolerancia a la salinidad para ser utilizado como material parental para programas de selección.

Palabras clave: Crecimiento de plántula, germinación, gramínea forrajera, marcadores moleculares.

Introduction

Salinity is one of the most serious problems affecting soils in arid and semi-arid areas around the world, affecting more than half the world's irrigated land and 20% of the cultivated land (Hasegawa and Bressan 2000). Peng et al. (2008) suggest that the widespread increases in saline soils and losses of arable lands, especially in the arid and semi-arid areas of most countries, could be the result of climate change, overgrazing, mowing and inappropriate farming systems. Salinization in soils affects crop growth as well as livestock production in pastoral regions (Peng et al. 2008). As the area affected by salinity is increasing, there is an urgent need to develop cultivars of forage species with an improved tolerance to salinity.

Saline stress involves both osmotic stress and ion toxicity (Munns 2002; De Lacerda et al. 2003), which interferes with ion homeostasis in plants (Huang and Redmann 1995; Huh et al. 2002), reducing growth by decreasing the rate of photosynthesis and leaf elongation (Pittaro et al. 2015). Salinity reduces and delays germination and emergence due to abnormal morphological, physiological and biochemical changes. It has been suggested that salt tolerance at a given growth stage is not strictly correlated with tolerance at other stages (Tobe et al. 2000) and it is generally accepted that plants are often more susceptible to salinity during germination and the seedling stage than as adults (Tober et al. 2007). Moreover, in order to survive saline conditions as an adult plant, pasture plants first have to overcome the inhibition of germination.

It is well known that the first step in establishing a breeding program is to demonstrate that there is enough variability for the target characteristic in the available germplasm collection (Vogel and Burson 2004). Morpho-physiological traits have been widely used to evaluate the genetic diversity for salt tolerance in crop species and over recent decades, molecular markers have been used extensively to study genetic diversity (Shahzad et al. 2012). In addition to advantages such as stability, reproducibility, high polymorphism and reliability, molecular markers are not influenced by the environment and many individuals can be screened at the same time. Markers such as Inter-simple sequence repeats (ISSR) have been utilized widely to investigate the genetic variations among populations in several species (Ganopoulos et al. 2015), especially grasses (Jurgenson 2005), using a primer designed from dinucleotide or tri-nucleotide simple repeats.

Panicum coloratum, a warm-season C_4 perennial grass, native to South Africa, is a cross-pollinated species and appears to be adapted to a wide range of soil conditions that makes it attractive for forage production in marginal areas. In particular, *P. coloratum* var. *makarikariense* can tolerate periods of drought followed by flooding (Tischler and Ocumpaugh 2004). A live germplasm collection belonging to INTA was assembled from sites where accessions had been established for more than 10 years and were considered adapted to different environmental and management conditions. Previous studies by our research group showed that *P. coloratum* is highly heterozygous (Armando et al. 2015) and that accessions in the collection represent panmictic populations (Armando et al. 2017). Aiming to develop a base population as the starting point for a breeding program, we screened the collection of *Panicum coloratum* var. *makarikariense* at INTA EEA Rafaela, focusing on the early stages of plant development, i.e. germination and seedling growth.

Since there were differences in origin and possibly exposure to particular selection pressures among accessions in the collection at INTA EEA Rafaela, we hypothesized that there is variability in life history traits and other characters such as salinity tolerance within and among them. In this study we assessed variability in response to salt concentration at germination and seedling stages and molecular variability by ISSR markers in the collection of *Panicum coloratum* var. *makarikariense* at INTA Rafaela in an endeavor to identify suitable accessions for use in a breeding program to improve salinity tolerance in the species.

Materials and Methods

Plant material

Four of the 7 accessions of the collection of *P. coloratum* var. *makarikariense* at INTA Rafaela Experiment Station (31°11'41" S, 61°29'55" W) were chosen for their good forage and seed production. A complete description of accessions in the collection is reported in Armando et al. (2013) and accessions we used are referred to as DF, ER, UCB and TS (TS corresponds to identified plants of cv. Bambatsi). In January–March 2014 seeds were collected from individuals constituting families of half-siblings from the 4 accessions giving a total of 18 mother plants (5 mother plants from DF and TS and 4 from ER and UCB).

Two different experiments were conducted to evaluate variability in response to increasing NaCl concentration at germination both within and among accessions of *P. coloratum* var. *makarikariense*. Incubation was performed in a growth chamber under 12-h photoperiod and at constant temperature (30 ± 4 °C). Seeds were monitored daily for 21 days and germinated seeds were recorded. A seed was considered germinated when the radicle was visible. For each experiment, conditions were set as explained below.

Salt tolerance at the germination stage

Experiment 1. From each of the 18 mother plants samples of 20 seeds were surface-sterilized with sodium hypochlorite solution (0.5%) and incubated in 5 cm diameter Petri dishes in 10 mL solutions of increasing NaCl concentrations (0, 100, 200, 300 and 400 mM NaCl) in a complete randomized block design with 3 replicates, i.e. 270 samples.

Experiment 2. For each of the 18 mother plants, samples of 20 seeds were placed in Petri dishes in 10 mL solutions of NaCl concentrations (0, 75 and 150 mM NaCl) in a complete randomized block design with 5 replicates and a total of 270 samples. As before, germination was monitored daily for 21 d, when seeds that had not germinated under the solutions containing salt were rinsed and placed in Petri dishes with distilled water for 10 d to evaluate their capacity to germinate under these conditions.

Analyzed variables

Germination percentage (GP) for each family was calculated as the ratio between the total number of germinated seeds and total number of seeds incubated. GP (% of control) (ratio of germination percentage in salinity treatment and mean germination percentage in control conditions) was calculated as the ratio between GP at each saline concentration and the GP at 0 mM NaCl. Mean germination time (MGT) was calculated as follows:

$$MGT = \Sigma (n \times d)/N,$$

where: n is the number of seeds germinated on day d; d is the number of days elapsed from the beginning of the test; and N is the total number of germinated seeds in the analyzed period (21 d) (Ellis and Roberts 1980; Raccuia et al. 2004).

The index of germination was estimated using Timson modified index of germination velocity (IG) as follows:

$$IG = \Sigma G/D$$

where: G is the seed germination percentage at one-day intervals; and D is the entire germination period analyzed (21 d) (Khan and Ungar 1984).

The recovery of germination percentage was calculated as follows:

$$R = [(a-b)/(c-b)]\times 100$$

where: a is the total number of seeds that germinated in a NaCl solution plus the number that germinated in distilled water after 10 d; b is the number of seeds that germinated in a NaCl solution; and c is the total number of seeds tested (Khan and Gulzar 2003; Wang et al. 2008).

Salt tolerance at the seedling stage

Seeds were grown in pots in a greenhouse during March to June at day/night temperatures of 34 °C/12 °C and light maintained at 623 µmol/m^2/sec. Seedlings with 3–4 leaves were placed in plastic trays filled with aerated full-strength Hoagland nutrient solution (Hoagland and Arnon 1950) and maintained under these conditions for 7 days. In salt treatments, salt concentration was then gradually increased (by adding NaCl in increments of 50 mM per day) until final concentration of 200 mM was reached. Nutrient solution without NaCl was used as the control treatment. There were 10 plants per family and treatment in a complete randomized design with 2 replicates. After 12 d of growth at the maximum NaCl concentration, 3 plants per treatment were withdrawn and Na^+ and K^+ concentrations in fully expanded leaves were determined by using high-performance liquid chromatography (HPLC). Na^+ and K^+ concentrations and the relationship Na^+:K^+ were expressed as the concentration of each ion in saline conditions over the concentration in control conditions, and referred to as Na^+ (cont), K^+ (cont) and Na^+:K^+ (cont). After 35-day periods, seedling numbers surviving (SN) were determined, 4 plants per family per treatment were removed and plant height (H) and leaf number (LN) were determined. Plants were then separated into aerial parts and roots, dried in an oven at 65 °C for 72 h until constant weight was reached and aerial dry weight (ADW) and root dry weight (RDW) were determined. For each morphological character measured, the reduction of growth (Red) produced by salt stress was estimated as follows (Griffa et al. 2010):

$$Red = [\Sigma (MXc-Xis)/MXc]/n$$

where: MXc is the median for control plants; Xis is the value of each salt-treated plant; and n is the number of replications.

Other variables were also calculated: relative water content of the aerial fraction [(AFW-ADW)/ADW]; and ratio between aerial dry weight and root dry weight (ADW:RDW).

Molecular characterization

The 18 mother plants of *P. coloratum* var. *makarikariense* were studied using ISSR markers. DNA extraction was carried out using a modified CTAB (cetyltrimethyl ammonium bromide) method. About 100 mg of homogenized leaf tissue was combined with 600 µL of CTAB buffer [100 mM Tris-HCl; 20 mM EDTA; 1.4 M NaCl; 1% p/v PVP (polyvinylpyrrolidone); 2% p/v CTAB; 0.2% v/v β-mercaptoethanol] and incubated at 60 °C for 60 min. After adding 600 µL of chloroform-isoamyl alcohol (24:1), the solution was centrifuged at 13,000 rpm for 10 min. This was followed by precipitation with 500 µL of ethanol, incubation at 20 °C overnight and centrifuging at 13,000 rpm for 2 min. The pellet was washed with 70% ethanol and dissolved in 200 µL of 1X TE (Tris-EDTA) buffer.

Five ISSR primers were used (Table 1). Amplification reactions were performed in 25 µL volume containing: 30 ng of DNA template; 2.5 mM $MgCl_2$; 0.2 mM of each dNTPs (generalized abbreviation for deoxytriphospate nucleotides); 1.2 µM of primer; and 1.25 U of Taq (*Thermus aquaticus*) DNA polymerase in 1X buffer. PCR (polymerase chain) reactions were carried out in Thermo cycler BioRad. Initial denaturation was at 94 °C for 3 min, followed by 39 cycles of 94 °C for 30 sec, 40 sec at annealing temperature, 40 sec at 72 °C and a final 5 min extension at 72 °C. Amplification products were resolved on 1.5% agarose gels, run at 70 V in 1X TBE (Tris-borate-EDTA) buffer for 160 min. They were visualized by staining with ethidium bromide and photographed under ultraviolet light.

Table 1. Polymorphic inter-simple sequence repeats (ISSR) used in this study.

ISSR	
Primer	Sequence 5′→3′
1 (7)	(CT)8TG
2 (14)	(CAC)4GC
3 (16)	(GACA)4
4 (19)	(GATA)2(GACA)2
5 (20)	(ACTG)2ACCGACTG

Statistical analyses

Salt tolerance at the germination stage. Residuals of GP, GP (% of control) and recovery were not normal. For this reason, total proportion of seeds that germinated was analyzed using generalized linear mixed models (PROC GLIMMIX using events/trials syntax) treating germination as binary (0 = did not germinate, 1 = germinated) (Cordeiro et al. 2014). Residual of variables MGT and IG were normal.

In the first assay, treatments, blocks, accessions and interactions between accessions and treatments were considered as fixed effects.

In the second assay we analyzed the distribution of variability in salinity tolerance in the collection. Block and treatment were considered as fixed effects. Accession and families nested within accession were considered as random effects. To evaluate recovery, accession effect was set as fixed.

Variable response to salt tolerance at the seedling stage and molecular characterization. Principal components analysis (PCA) based on the standardized Euclidean distance was performed with morphological and physiological variables as an exploratory method. Coordinate analysis (PCoA) based on the standardized Jaccard distance (Jaccard 1908) was performed with molecular markers. The following diversity parameters were estimated: genetic diversity; percentage of polymorphic loci (% P); number of alleles; mean effective alleles/locus; Nei's expected heterozygosity; number of bands; and percentage of polymorphic bands. For m locus, genetic diversity (D) was estimated as:

$$D = 1 - (1/m)\, \Sigma(j = 1\ldots m)\, \Sigma(i = 1\ldots l) p_{ij}^2$$

where: pij was the frequency of allele i in the locus j. For a locus, genetic diversity was estimated as: $D = 1 - \Sigma(i = 1\ldots l) p_i^2$. Then, these parameters were calculated for susceptible and tolerant families according to PCA. Correlation analysis correspondence between phenotypic and molecular matrices containing Euclidean and Jaccard, respectively, was investigated through a Mantel test (Mantel 1967). Statistical significance was determined using 1,000 random permutations. In this test, a correspondence measure (rxy) was calculated between the elements of 2 matrices, X and Y.

All analyses were performed in SAS version 9.2 (SAS 2010) and Infostat/Infogen (Balzarini and Di Rienzo 2011; Di Rienzo et al. 2011).

Results

Salinity tolerance at the germination stage

In order to evaluate the variable response to salinity among accessions at germination, 2 assays were carried out with different NaCl concentrations. In the first experiment, the interaction treatment x accession was significant (P = 0.014). While salinity generally reduced the number of germinated seeds, the magnitude of reduction differed among accessions (P<0.001) (Figure 1A). Germination was drastically reduced at concentrations above 200 mM NaCl and no seeds germinated at 400 mM NaCl (data not shown). No significant differences were detected in GP (% of control) with increasing salinity, although means were greater for accession ER at 100 and 200 mM NaCl (Figure 1B).

The second experiment was designed to determine whether variability in response to salinity was better explained by differences between accessions or differences between families within accessions at salt concentrations below 200 mM (Table 2). For all analyzed variables, variance due to accessions was null. Both GP and index of germination velocity (IG) decreased with increasing salt concentrations in the germination media (75 and 150 mM NaCl) with respect to control (0 mM NaCl, P<0.0001). The time necessary for a seed to germinate under saline conditions was longer than the time required for controls (P<0.0001). No significant differences between accessions were detected for GP, IG and MGT (Figure 2).

Table 2. Components of variance of germination percentage (GP), GP (% of control), mean germination time (MGT) and index of germination velocity (IG) of seeds of *Panicum coloratum* var. *makarikariense* in saline germination medium.

	GP	GP (% control)	MGT	IG
Accessions	0	0	0	0
Families	0.1171	0.1171	0.08552	32.1021

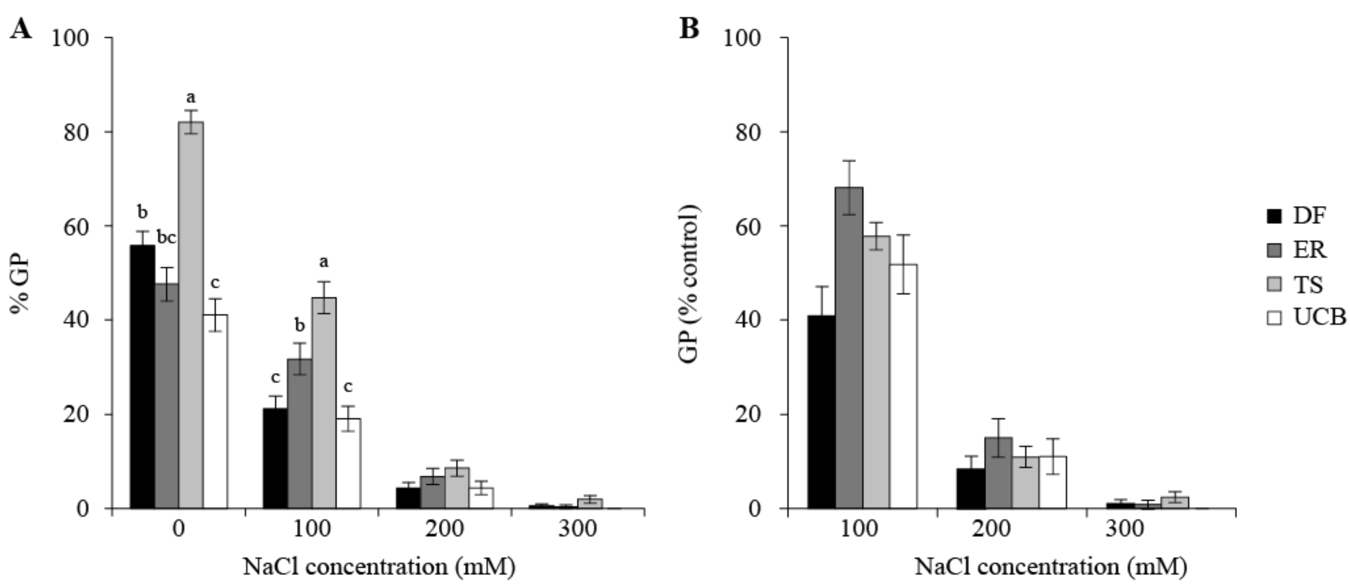

Figure 1. **A**. Germination % (GP) in accessions of *Panicum coloratum* var. *makarikariense* (DF, ER, TS and UCB) in 0, 100, 200 and 300 mM NaCl at 21 d. **B**. GP (% of control) at 100, 200 and 300 mM NaCl at 21 d. The data represent means ± s.e. Different letters indicate significant differences between accessions within salinity levels (P≤0.05).

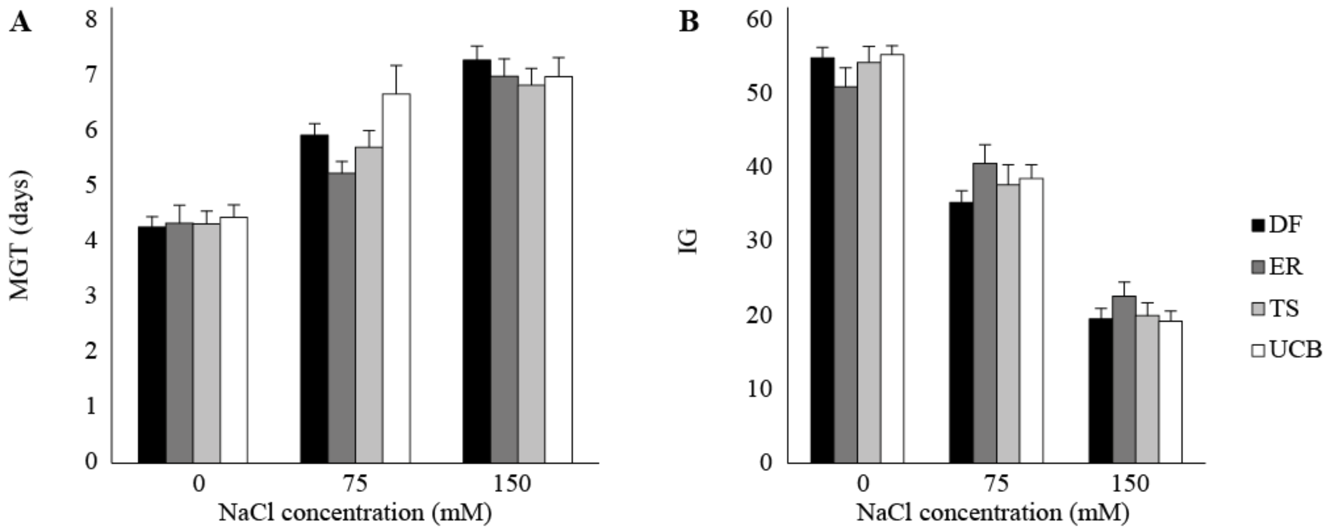

Figure 2. A. Mean germination time (MGT). **B**. Index of germination velocity (IG) in accessions of *Panicum coloratum* var. *makarikariense* (DF, ER, TS and UCB) in 0, 75 and 150 mM NaCl at 21 d. The data represent means ± s.e. No differences between accessions within salinity levels (P≥0.05) were detected.

There were significant (P<0.0001) differences between accessions in ability to germinate in distilled water after being exposed to saline conditions (Figure 3). While some remaining seeds of all accessions germinated, those of accessions TS and ER showed higher germination percentage than those of accessions DF and UCB after exposure to both 75 and 150 mM NaCl. The final germination percentage (FGP %), i.e. the total number of germinated seeds from an accession, including those germinating in saline conditions plus those germinating subsequently in distilled water, varied significantly between accessions. While final germination percentages in seeds in the control treatment, i.e. those exposed only to distilled water, were similar for all accessions, final germination percentages in seeds exposed to saline conditions and then to distilled water were significantly greater for ER and TS. Overall, while exposure to saline conditions reduced the total number of seeds which germinated (FGP %) for all accessions, the extent of the reduction was significant for only UCB and DF at 75 mM NaCl and for all 4 accessions at 150 mM NaCl.

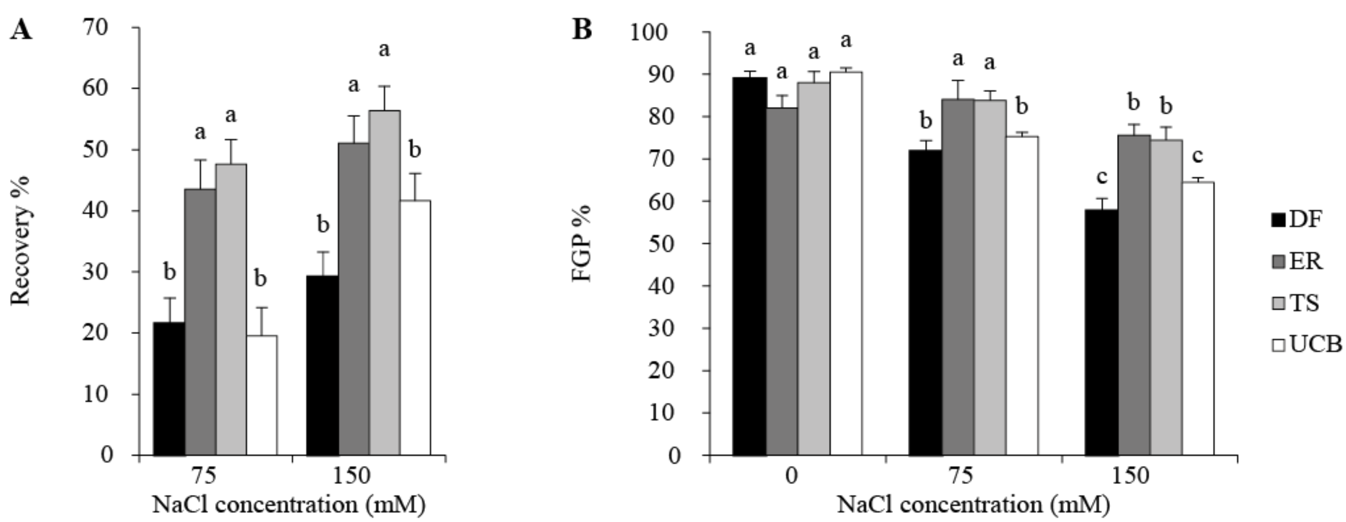

Figure 3. A. Recovery in germination of seed of accessions of *Panicum coloratum* var. *makarikariense* (DF, ER, TS and UCB) after exposure to 75 and 150 mM NaCl for 21 days then incubation in distilled water for 10 d (seeds germinating in 0 mM NaCl were not considered for recovery). **B.** Final germination percentage (FGP %) of seeds of accessions of *P. coloratum* var. *makarikariense* including seeds germinating after exposure to saline solutions for 21 days plus seeds germinating after subsequent exposure to distilled water for 10 days. The data represent means ± s.e. In each figure, different letters on columns indicate differences between accessions (P<0.05).

Salt tolerance at the seedling stage and molecular characterization

In order to evaluate the variation in salt tolerance at the seedling stage, an experiment comparing responses of seedlings of all accessions to control (0 mM NaCl) and saline conditions (200 mM NaCl) was carried out under hydroponic conditions. Salinity affected growth of plants, reducing parameters such as height (H), leaf number (LN) and seedling number (SN) (P<0.0001) and resulting in lower biomass of both aerial and root components (ADW and RDW) as depicted in Figure 4. Relative water content of the aerial fraction (AFW-ADW)/ADW was the only variable that did not show differences between families with increasing salinity (P = 0.35) (data not shown). Significant differences in plant growth due to exposure to salinity were detected between families (P<0.001) but not between accessions. In general, reductions in aerial and root growth (RedADW and RedRDW) were significantly lower (P<0.0001) in ER3, ER6, ER10, DF7, TS16 and TS23 than in other families (Figure 4).

Tissue concentrations of ions Na^+ and K^+ of plants growing in control and saline conditions are depicted in Table 3. Ion concentrations in saline conditions relative to those in controls showed significant differences among families in variables such as Na^+ (cont) (P<0.0001), K^+ (cont) (P = 0.032) (data not shown) and K^+:Na^+ (cont) (P<0.0001) (Figure 5).

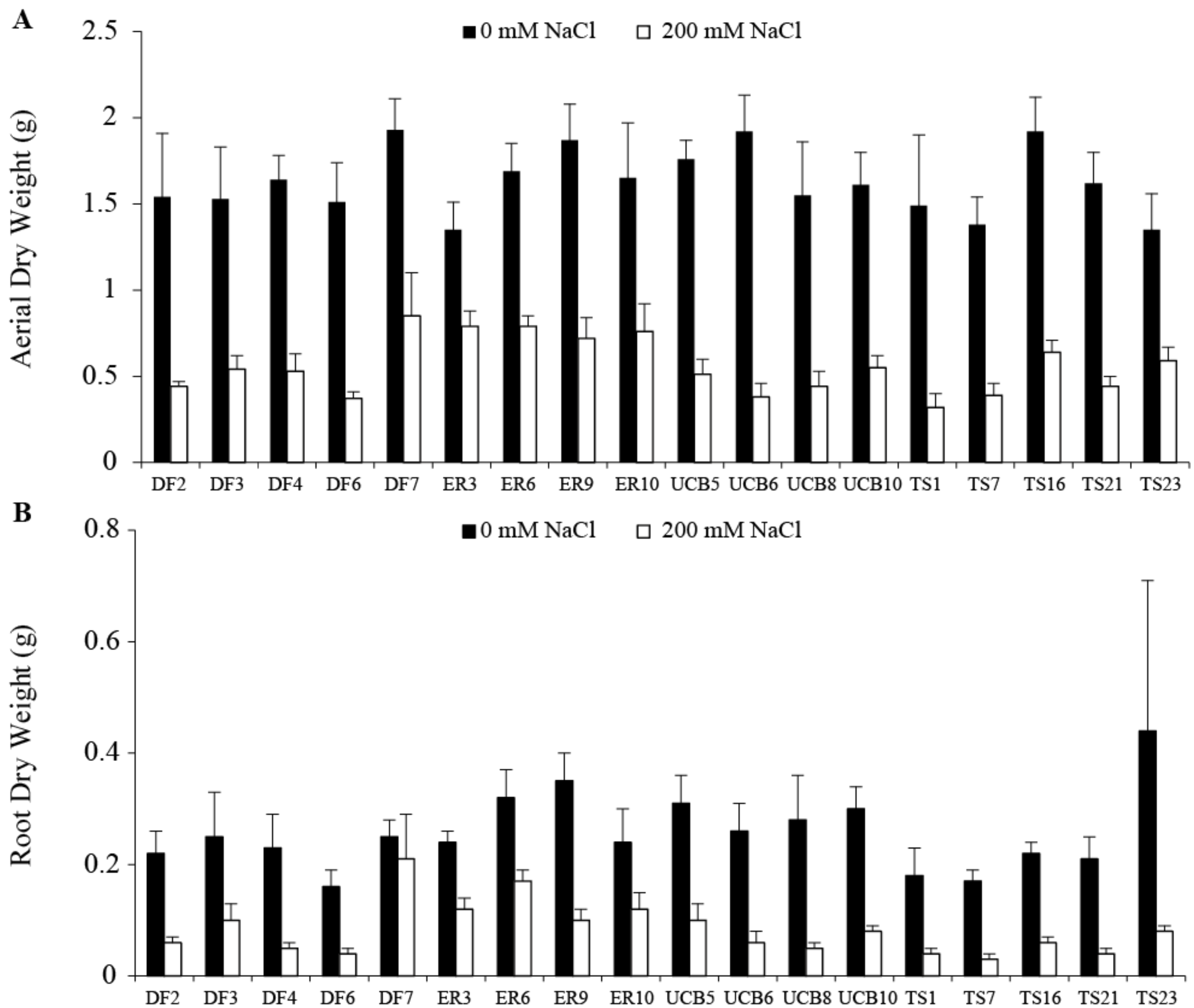

Figure 4. A. Aerial dry weight (ADW). **B.** Root dry weight (RDW) of plants of 18 families of 4 accessions of *Panicum coloratum* var. *makarikariense* in control (no NaCl in the medium) and 200 mM NaCl after 35 d. The data represent means ± s.e.

Table 3. Tissue concentrations of ions in leaves of *Panicum coloratum* var. *makarikariense* growing in saline (200 mM NaCl) and control (0 mM NaCl) hydroponic conditions in the greenhouse. Values are the means of determinations in 3 plants from the same half-sib family**.**

Family	Na^+ (nmol/g fresh weight)		K^+ (nmol/g fresh weight)	
	0 mM	200 mM	0 mM	200 mM
DF2	17.3 ± 2.0	673 ± 83.6	381 ± 33.6	225 ± 46.3
DF3	14.4 ± 2.0	902 ± 95.2	332 ± 47.2	267 ± 30.9
DF4	12.9 ± 2.6	452 ± 92.4	351 ± 30.6	145 ± 29.0
DF6	28.6 ± 7.3	427 ± 65.7	334 ± 43.1	157 ± 13.0
DF7	20.8 ± 3.4	452 ± 83.7	352 ± 32.4	142 ± 20.4
ER3	8.9 ± 0.6	457 ± 75.5	304 ± 88.3	176 ± 28.7
ER6	19.5 ± 2.8	393 ± 94.9	239 ± 37.1	183 ± 10.1
ER9	22.2 ± 5.3	539 ± 90.5	349 ± 49.7	174 ± 15.2
ER10	21.5 ± 9.7	380 ± 82.2	343 ± 21.3	236 ± 20.6
TS1	19.6 ± 4.3	634 ± 97.5	528 ± 93.9	192 ± 43.5
TS7	21.6 ± 3.2	723 ± 94.6	395 ± 59.1	196 ± 38.0
TS16	21.2 ± 6.1	464 ± 97.4	340 ± 15.3	167 ± 24.6
TS21	13.7 ± 2.3	647 ± 69.9	371 ± 73.3	192 ± 33.9
TS23	16.4 ± 3.5	573 ± 85.3	260 ± 34.0	176 ± 23.3
UCB5	11.1 ± 2.4	473 ± 58.8	376 ± 57.9	189 ± 31.7
UCB6	20.0 ± 9.1	486 ± 39.6	298 ± 57.2	130 ± 9.7
UCB8	16.8 ± 4.5	755 ± 92.8	362 ± 74.3	203 ± 28.5
UCB10	15.8 ± 2.5	713 ± 97.4	369 ± 37.7	212 ± 31.4

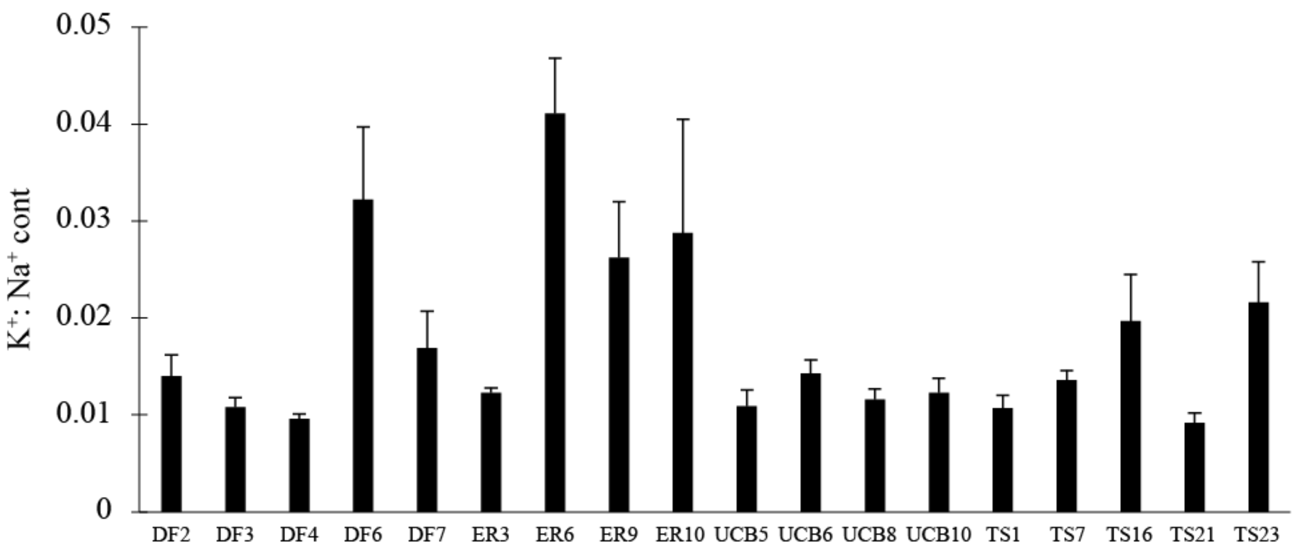

Figure 5. K^+:Na^+ ratio in tissue of plants grown for 21 days in saline 200 mM NaCl solutions relative to control plants for 18 families of *Panicum coloratum* var. *makarikariense*. The data represent means ± s.e.

Evidence of morphological differentiation among families in response to salinity is depicted in the PCA biplot (Figure 6). The first 2 components of the PCA explained 62.1% of the total variation. ADW showed high correlation with PC1, while SN, LN, RedADW and RedRDW were also well represented in PC1. Na^+ (cont) and K^+ (cont) were correlated with PC2 and K^+:Na^+ (cont); RedSN was relevant as well. A group of families with low reduction in growth, high values for morphological characters, especially in roots, and low accumulation of sodium in leaves with salinity, comprising ER3, ER6, ER9, ER10, DF7, TS16 and TS23, was clearly differentiated and distinguishable from the rest (Figure 6). Then, by means of the PCA we divided the families into 2 groups, i.e. susceptible and tolerant.

In order to characterize the molecular variability within the evaluated material, DNA from mother plants was extracted and analyzed with ISSR molecular markers. All primers used (5) were polymorphic and produced a total of 124 alleles. Genetic diversity (Jaccard) was 0.317, effective number of alleles per locus was 1.525 and Nei's expected heterozygosity and MGD were 0.326 and 0.775, respectively. When considering plants as belonging to groups (susceptible and tolerant) as differentiated in the PCA (Figure 6), genetic parameters were slightly different as shown in Table 4.

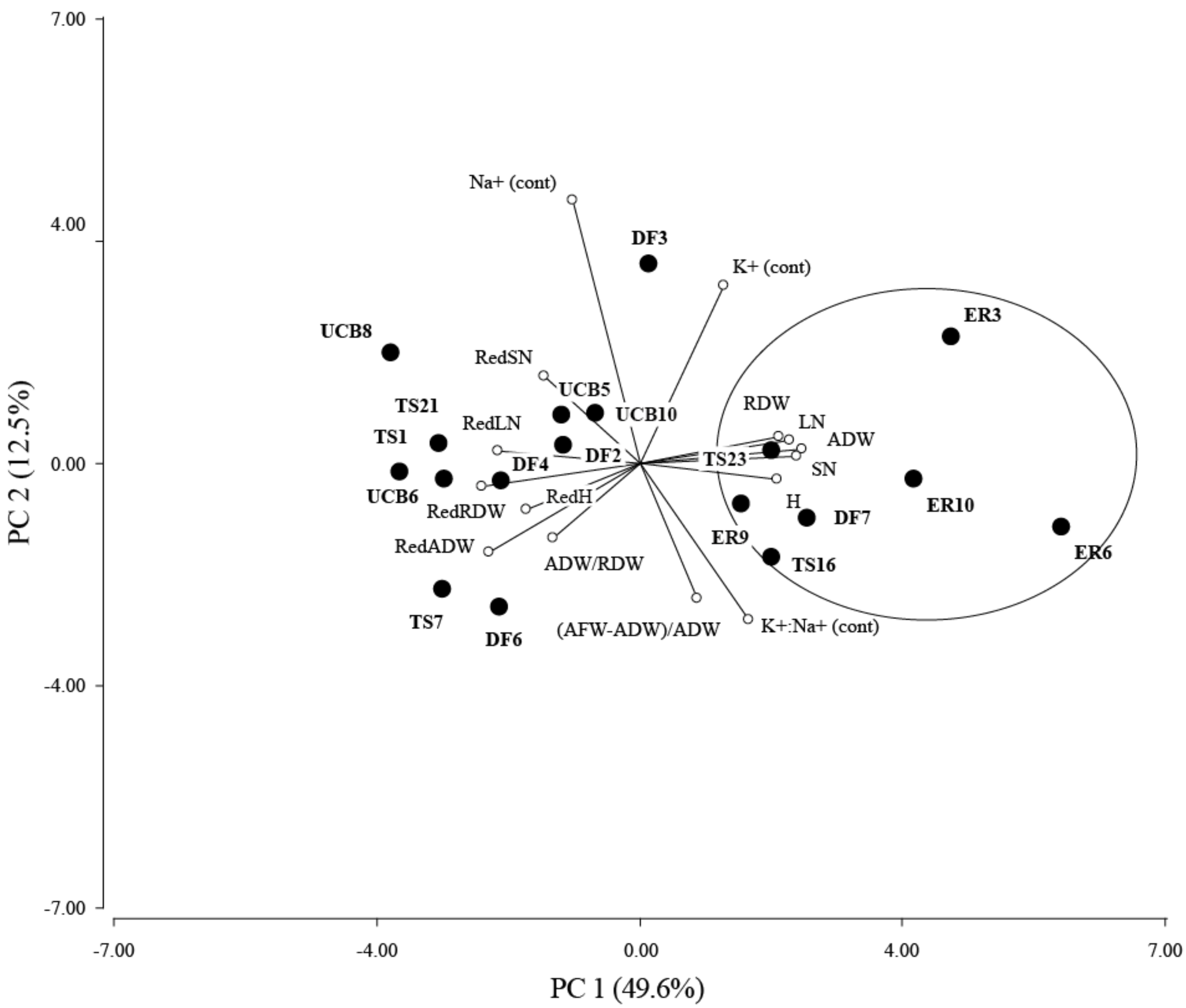

Figure 6. Variables and individual plot of principal components analysis (PCA) based on the Euclidean distance matrix calculated from 15 variables: aerial dry weight (ADW), root dry weight (RDW), number of seedlings (SN), leaf number (LN), height (H), reduction in growth of all variables (RedADW, RedRDW, RedH, RedSN, RedLN), (AFW-ADW)/ADW, (ADW:RDW) and Na^+ (cont), K^+ (cont) and K^+:Na^+ (cont), which are the ion concentrations in leaf tissue in saline conditions relative to the concentration in control conditions as explained in methods. Half-sib families (7) identified as tolerant according to morphological variables and ion concentration in green tissue are surrounded by the circle as explained in the text.

Table 4. Genetic parameters in plants categorized as tolerant and susceptible to salinity according to principal components analysis.

Parameter	Tolerant plants	Susceptible plants
Genetic diversity	0.284	0.293
Polymorphic loci	0.758	0.871
Total alleles	109	116
Mean effective alleles/locus	1.485	1.484
Nei`s expected heterozygosity	0.306	0.307
MGD (Jaccard distance)	0.790	0.754

PCoA biplot (Figure 7), based on the ISSR distance matrix, provided evidence of molecular differentiation among accessions but failed to distinguish between susceptible and tolerant plants. The first two coordinates of PCoA explained only 23.6% of the total variation.

Finally, the analysis between phenotypic (tested on the progeny) and molecular distances (tested on the maternal plants) by means of a Mantel test showed a significant positive but low correlation (r = 0.24; P = 0.038) between morphological and molecular distances.

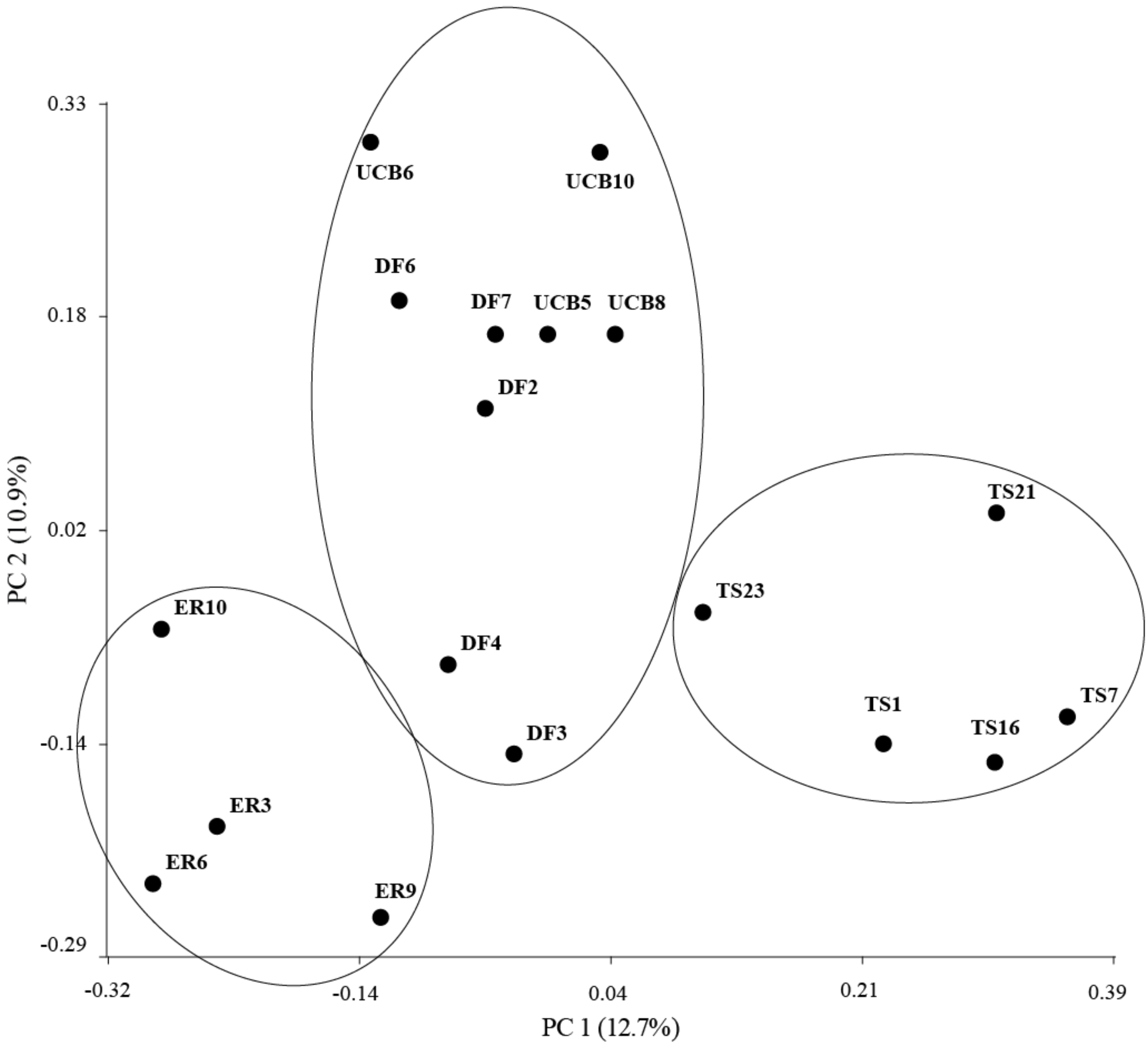

Figure 7. Principal coordinate analysis (PCoA) plot based on the individual ISSR distance matrix.

Discussion

As expected, germination was inhibited by an increase in salinity. These results are in agreement with previously reported reductions in germination caused by salinity stress in *Panicum turgidum* (El-Keblawy 2004) and *P. miliaceum* (Sabir and Ashraf 2008; Liu et al. 2015). Low to no germination at salt concentrations above 200 mM NaCl was also described by Taleisnik et al. (1999) in *Panicum coloratum var. coloratum* and other *Panicum* species (Hester et al. 2001; El-Keblawy 2004). However, Khan and Gulzar (2003) claimed that other grass species, like *Spartina alterniflora* and *Aeluropus lagopoides*, could tolerate salt concentrations of up to 500 mM. Patterns of response in other parameters associated with germination such as MGT and IG in related species were also similar to those reported by Liu et al. (2015).

Panicum coloratum as a species has been described as relatively tolerant of salinity (Pittaro et al. 2015), especially var. *makarikariense* (Tischler and Ocumpaugh 2004). However, in order to develop a breeding program to improve tolerance of salinity, it is crucial to evaluate the existence of genetic variability for this character (Vogel and Burson 2004). In addition, it is highly desirable to understand the variability structure in order to select appropriate accessions for crossing to produce the desirable outcomes.

We found that variability among families within accessions was higher than variation between accessions (Table 1). In fact, differences between accessions were hard to detect (Figure 1). This supports previous results by our research group that *Panicum coloratum* is a highly heterozygous, allogamous species, while accessions can be quite variable displaying a certain degree of phenotypic overlapping (Armando et al. 2015). A very similar pattern of diversity, in a variable related to response to an abiotic stress factor, is reported in the present study. Despite the fact that the accessions we studied were collected from non-saline areas (Armando et al. 2013) and differences in salinity tolerance between accessions were unexpected, a considerable level of variability in this attribute was encountered. Recovery tests are usually used to determine whether non-germinated seeds following exposure to saline conditions are killed or germination is merely prevented by saline stress (Guan et al. 2009). In our assay, many seeds, which failed to germinate in NaCl solution, maintained the ability to germinate after transfer to distilled water. This result suggests that the inhibitory effects of salinity could be due to osmotic effects and not to sodium toxicity. Following exposure of seeds to saline solution, salt would enter the seed causing an inhibition of germination, although it was not directly toxic, allowing seeds to recover afterwards in pure water (Zhang et al. 2012). This ability of seeds to remain viable after exposure to salinity and to germinate when saline stress is reduced is an important mechanism enabling persistence under a stressful unpredictable environment (Keiffer and Ungar 1995). Although all accessions had the capacity to recover, differences between accessions were detected. In particular, the superior recovering ability of seeds from ER and TS (Figure 3A) makes these accessions potential candidates for selecting genetic material that can germinate when saline conditions are removed, as might occur after a rainy season preceded by a dry period.

As is the case with germination, salt tolerance during early seedling stages is critical for the establishment of plants in salty soils (Al-Khateeb 2006). In our assay, saline conditions suppressed seedling growth in all evaluated families but the magnitude of the suppressions varied markedly. In addition, plants growing in saline solutions accumulated additional sodium in their leaves, while, in general, potassium level was decreased. The reduction in the ratio of K^+:Na^+ in response to salinity has been reported for other forage species such as *Panicum antidotale* (Ahmad et al. 2010).

In our experiments, we encountered variability in almost all characters between families at the seedling stage under saline conditions, indicating that plants suffered damage due to high salt concentration with different levels of injury. Morphological and biochemical variables allowed us to differentiate tolerant from susceptible families as shown in Figure 6. We identified tolerant plants as those producing the most biomass under salinity and showing lower levels of damage (reduction in growth). These families also showed lower values for ADW:RDW, indicating preferential allocation of biomass to roots, and also showed comparatively less damage at root level. This characteristic is crucial in saline areas because the main function of roots is to absorb water and nutrients. The lower decrease of RDW relative to ADW is an indicator of an adaptation to continue to absorb water and nutrients, albeit at a level below the optimum, even under salt stress conditions. Additionally, accumulation of toxic ions like Na^+ in roots increases as root biomass increases, thus minimizing its negative effects in the shoot (Marschner 1995; Acosta-Motos et al. 2005). In general, the family groups pointed out as salt-tolerant in Figure 6 also showed high values of K^+:Na^+(cont) (Figure 5) indicating lower amounts of Na^+ in leaf tissue than the susceptible ones.

Characterization by molecular markers showed high levels of variability in the germplasm collection, although utilization of more markers would have depicted the variation in the available germplasm more clearly. Actually, the first 2 coordinates in the PCoA (Figure 7) explained only 23.6% of total variation. Despite the low representation of the variability in the first 2 axes, plants congregate in the plot according to their provenance, i.e. the accession that they belonged to. This pattern of distribution of genetic variation (i.e. a higher proportion between accessions and a lower proportion within accessions) is not normally expected for an allogamous plant but it is in agreement with previous results from our research group (Armando et al. 2015).

Molecular analysis did not allow differentiation based on salinity tolerance. The low correspondence between phenotypic and molecular variation (r = 0.26) was not unexpected, since most DNA markers constitute a sample of random genomic sites in which polymorphism has no effect on phenotypic characters (Holderegger et al. 2006). Given that *P. coloratum* is an allogamous species, considerable levels of genetic variation are required in a base population prior to performing selection to avoid problems due to inbreeding depression (Vogel and Burson 2004). This should not be a problem with this set of individuals since, when ER3, ER6, ER9, ER10, TS16, TS23 and DF7 (tolerant plants according to PCA) were considered in a separate group, they retained relatively high levels of variation, pointing out that this population, although small, could be used in a breeding program to improve tolerance to salinity (Table 2).

In this study, we reported considerable variation in salt tolerance in a germplasm collection of *P. coloratum* var. *makarikariense* at both germination and seedling stages, as well as variability in molecular characterization. As expected for an allogamous species, variability between families within accessions was higher than between accessions for characters related to germination. Phenotypic characterization at the seedling stage allowed differentiation between tolerant and susceptible families by means of morphological traits and concentrations of ions in the leaves. This tolerant material, although coming from a low number of mother plants (n = 7), provides considerable levels of variability to carry out further cycles of selection. These preliminary findings can be tested by incorporating selected accessions in breeding programs to improve salinity tolerance in this already valuable pasture species.

Acknowledgments

A fellowship to LC from the National Research Council of Argentina (CONICET) is gratefully acknowledged. The authors thank N. De Marco, L. Iacopini, M. Giordano, V. Pilatti and C. Thompson for their advice and help in the assays.

References

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

Acosta-Motos JR; Diaz-Vivancos P; Álvarez S; Fernández-García N; Sánchez-Blanco MJ; Hernández JA. 2015. NaCl-induced physiological and biochemical adaptive mechanisms in the ornamental *Myrtus communis* L. plants. Journal of Plant Physiology 183:41–51. DOI: 10.1016/j.jplph.2015.05.005

Ahmad MSA; Ashraf M; Ali Q. 2010. Soil salinity as a selection pressure is a key determinant for the evolution of salt tolerance in Blue Panicgrass (*Panicum antidotale* Retz.). Flora 205:37–45. DOI: 10.1016/j.flora.2008.12.002

Al-Khateeb SA. 2006. Effect of salinity and temperature on germination, growth and ion relations of *Panicum turgidum* Forssk. Bioresource Technology 97:292–298. DOI: 10.1016/j.biortech.2005.02.041

Armando LV; Carrera AD; Tomas MA. 2013. Collection and morphological characterization of *Panicum coloratum* L. in Argentina. Genetic Resources and Crop Evolution 60:1737–1747. DOI: 10.1007/s10722-013-9982-3

Armando LV; Tomás MA; Garayalde AF; Carrera AD. 2015. Assessing the genetic diversity of *Panicum coloratum* var. *makarikariense* using agro-morphological traits and microsatellite-based markers. Annals of Applied Biology 167:373–386. DOI: 10.1111/aab.12234

Armando LV; Tomás MA; Garayalde AF; Carrera AD. 2017. Effect of pollination mode on progeny of *Panicum coloratum* var. *makarikariense*: Implications for conservation and breeding. Tropical Grasslands-Forrajes Tropicales 5:117–128. DOI: 10.17138/TGFT(5)117-128

Balzarini M; Di Rienzo J. 2011. Info-Gen: Software para análisis estadístico de datos genéticos. Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Argentina.

Cordeiro MA; Moriuchi KS; Fotinos TD; Miller KE; Nuzhdin SV; von Wettberg EJ; Cook DR. 2014. Population differentiation for germination and early seedling root growth traits under saline conditions in the annual legume *Medicago truncatula* (Fabaceae). American Journal of Botany 101:488–498. DOI: 10.3732/ajb.1300285

De Lacerda CF; Cambraia J; Oliva MA; Ruiz HA; Prisco JT. 2003. Solute accumulation and distribution during shoot and leaf development in two sorghum genotypes under salt stress. Environmental and Experimental Botany 49:107–120. DOI: 10.1016/S0098-8472(02)00064-3

Di Rienzo JA; Casanoves F; Balzarini MG; Gonzalez L; Tablada M; Robledo CW. 2011. InfoStat, Versión 2011. Grupo InfoStat, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Argentina. infostat.com.ar

El-Keblawy A. 2004. Salinity effects on seed germination of the common desert range grass, *Panicum turgidum*. Seed Science and Technology 32:873–878. DOI: 10.15258/sst.2004.32.3.24

Ellis RH; Roberts EH. 1980. Towards a rational basis for testing seed quality. In: Hebblethwaite PD, ed. Seed production. Butterworths, London, UK. p. 605–635.

Ganopoulos I; Kalivas A; Kavroulakis N; Xanthopoulou A; Mastrogianni A; Koubouris G; Madesis P. 2015. Genetic diversity of Barbary fig (*Opuntia ficus-indica*) collection in Greece with ISSR molecular markers. Plant Gene 2:29–33. DOI: 10.1016/j.plgene.2015.04.001

Griffa S; Ribotta A; López Colomba E; Tommasino E; Carloni E; Luna C; Grunberg K. 2010. Evaluation of seedling biomass and its components as selection criteria for improving salt tolerance in Buffel grass genotypes. Grass and Forage Science 65:358–361. DOI: 10.1111/j.1365-2494.2010.00754.x

Guan B; Zhou D; Zhang H; Tian Y; Japhet W; Wang P. 2009. Germination responses of *Medicago ruthenica* seeds to salinity, alkalinity, and temperature. Journal of Arid Environments 73: 135–138. DOI: 10.1016/j.jaridenv.2008.08.009

Hasegawa P; Bressan R. 2000. Plant cellular and molecular responses to high salinity. Annual Review of Plant Physiology and Plant Molecular Biology 51:463–499. DOI: 10.1146/annurev.arplant.51.1.463

Hester MW; Mendelssohn IA; Mckee KL. 2001. Species and population variation to salinity stress in *Panicum hemitomon*, *Spartina patens*, and *Spartina alterniflora*: Morphological and physiological constraints. Environmental and Experimental Botany 46:277–297. DOI: 10.1016/S0098-8472(01)00100-9

Hoagland DR; Arnon DI. 1950. The water-culture method for growing plants without soil. California Agricultural Experiment Station Circular 347. University of California, Berkeley, CA, USA. goo.gl/Mee8fK

Holderegger R; Kamm U; Gugerli F. 2006. Adaptative vs. neutral genetic diversity: Implications for landscape genetics. Landscape Ecology 21:797–807. DOI: 10.1007/s10980-005-5245-9

Huang J; Redmann RE. 1995. Salt tolerance of *Hordeum* and *Brassica* species during germination and early seedling growth. Canadian Journal of Plant Science 75:815–819. DOI: 10.4141/cjps95-137

Huh GH; Damsz B; Matsumoto TK; Reddy MP; Rus AM; Ibeas JI; Narasimhan ML; Bressan RA; Hasegawa PM. 2002. Salt causes ion disequilibrium-induced programmed cell death in yeast and plants. The Plant Journal 29:649–659. DOI: 10.1046/j.0960-7412.2001.01247.x

Jaccard P. 1908. Nouvelles recherches sur la distribution florale. Bulletin de la Société Vaudoise des Sciences Naturelles 44:223–270. goo.gl/82tFDG

Jurgenson J. 2005. Analysis of genetic diversity of Iowa's native plant species using the Beckman CEQ 8000 genetic analyzer. The Iowa Living Roadway Trust Fund, Ames, IA, USA. goo.gl/iXnLxS

Keiffer CW; Ungar IA. 1995. Germination responses of halophyte seeds exposed to prolonged hypersaline conditions. In: Khan MA; Ungar IA, eds. Biology of salt tolerant plants. Department of Botany, University of Karachi, Karachi, Pakistan. p. 43–50.

Khan MA; Ungar IA. 1984. The effect of salinity and temperature on the germination of polymorphic seeds and growth of *Atriplex triangularis* Willd. American Journal of Botany 71:481–489. DOI: 10.2307/2443323

Khan MA; Gulzar S. 2003. Light, salinity, and temperature effects on the seed germination of perennial grasses. American Journal of Botany 90:131–134. DOI: 10.3732/ajb.90.1.131

Liu M; Qiao Z; Zhang S; Wang Y; Lu P. 2015. Response of broomcorn millet (*Panicum miliaceum* L.) genotypes from semiarid regions of China to salt stress. The Crop Journal 3:57–66. DOI: 10.1016/j.cj.2014.08.006

Mantel N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Research 27:209–220. goo.gl/2pu2xL

Marschner H, ed. 1995. Mineral nutrition of higher plants. 2nd Edn. Academic Press, London, UK. DOI: 10.1016/B978-0-12-473542-2.X5000-7

Munns R. 2002. Comparative physiology of salt and water stress. Plant, Cell & Environment 25:239–250. DOI: 10.1046/j.0016-8025.2001.00808.x

Peng YL; Gao ZW; Gao Y; Liu GF; Sheng LX; Wang DL. 2008. Eco-physiological characteristics of alfalfa seedlings in response to various mixed salt-alkaline stresses. Journal of Integrative Plant Biology 50:29–39. DOI: 10.1111/j.1744-7909.2007.00607.x

Pittaro G; Cáceres L; Bruno C; Tomás A; Bustos D; Monteoliva M; Ortega L; Taleisnik E. 2015. Salt tolerance variability among stress-selected *Panicum coloratum* cv. Klein plants. Grass and Forage Science 71:683–698. DOI: 10.1111/gfs.12206

Raccuia SA; Cavallaro V; Melilli MG. 2004. Intraspecific variability in *Cynara cardunculus* L. var. *sylvestris* Lam. Sicilian populations: Seed germination under salt and moisture stresses. Journal of Arid Environments 56:107–116. DOI: 10.1016/S0140-1963(03)00006-5

Sabir P; Ashraf M. 2008. Inter-cultivar variation for salt tolerance in Proso millet (*Panicum miliaceum* L.) at the germination stage. Pakistan Journal of Botany 40:677–682. goo.gl/cy6wSW

SAS. 2010. SAS Users' guide, version 9.3. Statistical Analysis System (SAS) Institute Inc., Cary, NC, USA.

Shahzad A; Ahmad M; Iqbal M; Ahmed I; Ali GM. 2012. Evaluation of wheat landrace genotypes for salinity tolerance at vegetative stage by using morphological and molecular markers. Genetics and Molecular Research 11: 679–692. DOI: 10.4238/2012.March.19.2

Taleisnik E; Pérez H; Córdoba A; Moreno H; García Seffino L; Arias C; Grunberg K; Bravo S; Zenoff A. 1999. Salinity effects on the early development stages of *Panicum coloratum*: Cultivar differences. Grass and Forage Science 53:270–278. DOI: 10.1046/j.1365-2494.1998.00139.x

Tischler CR; Ocumpaugh WR. 2004. Kleingrass, blue panic and vine mesquite. In: Moser LE; Burson BL; Sollenberger LE, eds. Warm-season (C4) grasses. Agronomy Monograph 45. ASA, CSSA, SSA, Madison, WI, USA. p. 623–649. DOI: 10.2134/agronmonogr45.c18

Tobe K; Li X; Omasa K. 2000. Seed germination and radicle growth of a halophyte, *Kalidium caspicum* (Chenopodiaceae). Annals of Botany 85:391–396. DOI: 10.1006/anbo.1999.1077

Tober D; Duckwitz W; Sieler S. 2007. Plant materials for salt-affected sites in the Northern Great Plains. Natural Resources Conservation Service Technical Note. United States Department of Agriculture, Bismarck, ND, USA. goo.gl/HBNWTm

Vogel KP; Burson BL. 2004. Breeding and genetics. In: Moser LE; Burson BL; Sollenberger LE, eds. Warm-season (C4) grasses. Agronomy Monograph 45. ASA, CSSA, SSSA, Madison, WI, USA. p. 51–94. DOI: 10.2134/agronmonogr45.c3

Wang L; Huang Z; Baskin CC; Baskin JM; Dong M. 2008. Germination of dimorphic seeds of the desert annual halophyte *Suaeda aralocaspica* (Chenopodiaceae), a C4 plant without Kranz anatomy. Annals of Botany 102:757–769. DOI: 10.1093/aob/mcn158

Zhang H; Irving LJ; Tian Y; Zhou D. 2012. Influence of salinity and temperature on seed germination rate and the hydrotime model parameters for the halophyte, *Chloris virgata*, and the glycophyte, *Digitaria sanguinalis*. South African Journal of Botany 78:203–210. DOI: 10.1016/j.sajb.2011.08.008

(Received for publication 31 January 2018; accepted 7 June 2018; published 30 September 2018)

DOI: 10.17138/TGFT(6)148-157

Research Paper

How does seed size of *Arachis pintoi* affect establishment, top-growth and seed production?

¿Cómo afecta el tamaño de la semilla el establecimiento, la biomasa aérea y la producción de semilla de Arachis pintoi*?*

GISELLE M.L. DE ASSIS[1], DANIELA P. MIQUELONI[2], HELLEN S.F.S. AZÊVEDO[2] AND JUDSON F. VALENTIM[1]

[1]*Empresa Brasileira de Pesquisa Agropecuária, Embrapa Acre, Rio Branco, Acre, Brazil.* www.embrapa.br
[2]*Universidade Federal do Acre, Rio Branco, Acre, Brazil.* www.ufac.br

Abstract

The adoption of *Arachis pintoi* in mixed pastures in the humid tropics remains limited to specific success cases, mainly because of high seed cost. The search for methods to reduce these costs is a key challenge towards promoting wider adoption of this legume in livestock production systems in the tropics. One possible option is to select for smaller seeds, which would allow lower sowing rates, while ensuring similar plant numbers. Alternatively, high seed production costs could be offset by utilizing forage from seed production fields for hay or silage prior to seed harvest. This study evaluated the effects of seed size on crop performance of *A. pintoi* cv. BRS Mandobi in a tropical forage + seed production system, plus the effects of harvesting forage during the growth stage on seed production. Parameters measured were: ground cover, height, pest and disease incidence, total forage and leaf yield plus seed yield and seed sizes. Smaller seeds resulted in morphologically smaller plants and lower forage mass during the initial phase of crop establishment. However, seed size had no effect on ground cover at the end of the establishment period or on seed production and quality. Harvesting forage during the growth cycle had no effect on seed production. This indicates the possibility of harvesting forage from seed crops of *A. pintoi* during growth without jeopardizing seed yields as a means of offsetting high costs of seed production. However, the study has failed to provide conclusive evidence whether variation in seed size in BRS Mandobi is mainly genetic or a response to micro-environmental conditions. Further studies with individual plants from BRS Mandobi are necessary to determine the heritability of seed size.

Keywords: Aerial biomass, forage peanut, ground cover, seed quality.

Resumen

La adopción de *Arachis pintoi* en pasturas mixtas en el trópico húmedo se limita a casos específicos de éxito, principalmente debido al alto costo de la semilla. La búsqueda de métodos para reducir esos costos es un desafío clave para promover la adopción a gran escala de esta leguminosa en sistemas de producción pecuaria en el trópico. Una posible opción es seleccionar semillas más pequeñas, lo que permitiría tasas de siembra más bajas, pero un número de plantas similar. Además, la utilización de la masa forrajera de los campos de producción de semillas para heno o ensilaje puede compensar los altos costos de producción de semillas. Este estudio se realizó en Rio Branco, Acre, Brasil con el fin de: (1) evaluar el efecto del tamaño de la semilla en el establecimiento y la producción de *A. pintoi* cv. BRS Mandobi en un sistema tropical de producción de forraje + semilla, y (2) medir los efectos de la cosecha de forraje en la producción de semilla. Los parámetros evaluados fueron: cobertura del suelo, altura de planta, incidencia de plagas y enfermedades, producción de forraje total y rendimiento foliar; además, rendimiento y tamaño de semilla. Las semillas pequeñas produjeron igualmente plantas morfológicamente pequeñas

Correspondence: Giselle Mariano Lessa de Assis, Embrapa Acre, Rodovia BR 364, km 14, PO Box 321, Rio Branco CEP 69900-970, AC, Brazil.
Email: giselle.assis@embrapa.br

y con menor masa de forraje durante el establecimiento. Sin embargo, el tamaño de la semilla no tuvo ningún efecto sobre la cobertura del suelo al final del período de establecimiento o sobre el rendimiento y la calidad de la semilla producida. La cosecha de forraje durante el período de crecimiento de *A. pintoi* no afectó la producción de semillas. Esto indica que la cosecha de forraje en los cultivos de semillas durante el crecimiento puede contribuir a compensar los altos costos de la producción de semillas. Los resultados no son concluyentes sobre si la variabilidad en el tamaño de la semilla en BRS Mandobi es debida principalmente a la genética o las condiciones microambientales. Se necesitan estudios con plantas individuales para inferir sobre la heredabilidad del tamaño de la semilla.

Palabras clave: Calidad de semilla, cobertura de suelo, maní forrajero, producción de forraje.

Introduction

Despite research and development efforts during the 1990s and 2000s (Argel 1994; Ramos et al. 2010; Assis and Valentim 2013), the adoption of forage peanut (*Arachis pintoi* Krapov. & W.C. Greg.) for use in mixed pastures in the humid tropics and subtropics remains limited to specific successful cases (Shelton et al. 2005). The greatest barrier to wider adoption is limited availability and high cost of propagation material, mainly seeds. The major challenge for expanding adoption is to increase the supply and reduce the cost of seed, as already pointed out more than 2 decades ago by Ferguson (1994).

High cost of seed production is due to the difficulty in harvesting the seeds, which are produced below the soil surface, like all species of *Arachis*, and seeds do not remain attached to the plant, as occurs with peanut (*Arachis hypogaea* L.) (Ferguson 1994). Seeds need to be sifted from the soil and recovered. In addition, seeds of *A. pintoi* are relatively large, when compared with other tropical forage species, and require a higher sowing rate to achieve acceptable plant numbers. A sowing rate of 12 kg of viable pure seeds/ha is recommended currently to establish mixed grass-*A. pintoi* cv. BRS Mandobi pastures (Abreu et al. 2012). Reducing the sowing rate, as long as there are adequate numbers of seeds per kilogram, would reduce sowing costs.

Variation in size of BRS Mandobi seeds does exist, as shown by Assis et al. (2013) in the Western Brazilian Amazon, and there are possibilities of intra-cultivar selection for this characteristic (Assis et al. 2016). In general, larger seeds have higher germination and seedling vigor than smaller seeds (Beckert et al. 2000), but this initial advantage disappears rapidly during the later stages of establishment (Bredemeier et al. 2001). However, how seed size affects establishment, above-ground dry matter yield and seed production of forage peanut remains unknown.

Another way for seed producers to offset the high cost of producing seed is to add value to the system, e.g. by grazing or cutting forage for hay or silage during the period of vegetative growth before harvesting a seed crop. Such a system could be considered as a forage + seed production system under integrated crop-livestock systems. Crop management is an important factor in seed production, since seed yield tends to decrease with increased frequency of harvesting forage (Bortolini et al. 2004; Awad et al. 2013). In Costa Rica, Argel (1994) found that frequent cutting intervals for forage (every 2 months) reduced seed production of forage peanut, and this effect occurred even at intervals as long as 8 months, with the response depending on the genotype.

The objectives of this study were to evaluate the influences of seed size on establishment, development and seed production of *A. pintoi* cv. BRS Mandobi in a monospecific stand, as well as performance of this legume in a dual-purpose production system (forage and seeds) in the Brazilian humid tropics.

Materials and Methods

The study extended from November 2008 to October 2009 at the Experimental Station of the Agroforestry Research Center of the Brazilian Agricultural Research Corporation – Embrapa, located in Rio Branco, AC, Brazil [10°01'34" S, 67°42'13" W (WGS 84); elevation 160 masl]. The climate is classified by Köppen as Awi (hot and humid), with maximum temperature of 31 °C and minimum of 21 °C, mean annual precipitation of 1,900 mm, mean relative humidity of 80% and a rainy season from October to May and dry season from June to September (Figure 1). The soil of the experimental area is an Oxisol, and chemical analyses at 0–20 cm depth are: organic matter, 1.3%; pH in water, 5.4; Ca, 1.6 cmol/kg; Mg, 0.4 cmol/kg; K, 0.1 cmol/kg; Al, 1.0 cmol/kg; P (Mehlich 1), 2.0 mg/kg; cation exchange capacity, 5.4 cmol/kg; and base saturation, 38.6%.

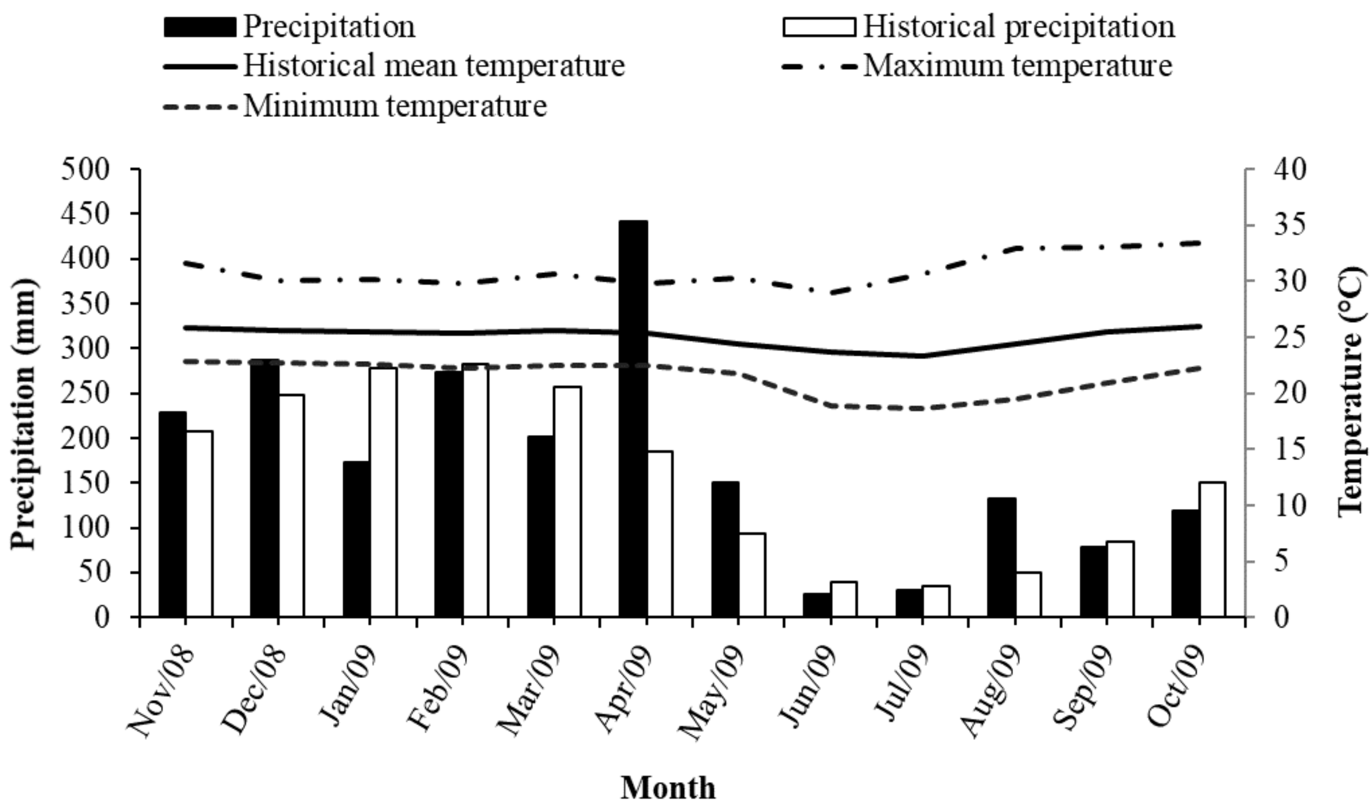

Figure 1. Temperature and precipitation during the experimental period (November 2008 to October 2009) and historical data (1969–2014) (INMET 2015).

The experimental design was a randomized complete block design, with treatment combinations of 3 seed sizes (small, medium and large) and either harvesting forage at 3 separate times or not harvesting forage before reaping the seed crop, with 4 replications. While *A. pintoi* is planted using the entire fruit, i.e. seed plus pod, we use the term 'seed' as a substitute for 'fruit', i.e. the propagation unit. The seed lot of *A. pintoi* cv. BRS Mandobi was harvested in July 2007 and stored for 17 months, a period considered long enough to overcome seed dormancy naturally without physical treatment. After this period, we measured pure seeds with a digital caliper and separated them into 3 size categories (treatments), based on the product of seed length by seed width: small, ≤61 mm^2; medium, 62–88 mm^2; and large, >88 mm^2. Seed numbers per kilogram, according to size categories, were: small, 10,070; medium, 6,250; and large, 4,700 seeds.

Seeds were sown on 13 November 2008 in 3 x 3 m plots, with 50 cm spacing between rows and 14 cm between plants within rows, in furrows at 3 cm soil depth, with 21 seeds/row for all treatments, which corresponds with sowing rates of 14, 22 and 30 kg/ha for small, medium and large seeds, respectively. Triple superphosphate (21.8 kg P/ha), potassium chloride (33.2 kg K/ha) and Fritted Trace Elements (40 kg FTE/ha) were applied at sowing.

The following aspects were examined: establishment period; leaf morphological characterization; forage and seed production (forage + seed evaluation); and seed quality (germination rate and seedling vigor), in order to evaluate the effects of seed size on forage peanut growth and its influence on morphological characteristics of plants plus seed production and quality. All statistical analyses, consisting of analysis of variance, regression analysis and comparison of means, were conducted using the Sisvar computer program (version 5.3) (Ferreira 2014).

Establishment period

The establishment period was from November 2008 to March 2009 and involved evaluation of the following parameters: incidence of pests and diseases; plant vigor; and flowering intensity. Incidence of pests and diseases was evaluated visually using the scale: 0 = no damage; 1 = slight damage on ≤50% of plants; 2 = slight damage on 51–100% of plants; 3 = moderate damage on ≤50% of plants; 4 = moderate damage on 51–100% of plants; and 5 = severe damage. Therefore, the score allocated was a combination of the extent of damage, in terms of the affected area within the plot, and the degree of its severity. Plant vigor assessment was based on a 1–10 scale, with: 1 = very poor vigor; and 10 = excellent vigor. Plant flowering intensity was estimated visually based on the percentage of plants with flowers: 0 = no flowering; 1 = 1–20% of plants flowering; 2 = 21–40%; 3 = 41–60%; 4 = 61–80%; 5 = 81–100% flowering. During the establishment period, ground cover was assessed using a 1 x 1 m wooden frame subdivided into smaller squares of 10 x 10 cm. Plant height was also determined, based on measurements at 3 different points in each plot, in order to obtain the average height of the stand.

Leaf morphological characterization

Morphological characterization of leaves occurred in a single evaluation, before the first forage harvest, in March 2009. The following measurements were made on 10 plants (one leaflet of each type per plant) in each replication of each treatment: basal leaflet length and width (BLL and BLW); and apical leaflet length and width (ALL and ALW). Petiole length (PL) was determined as the mean of measurements on 5 leaves. All variables were measured in millimeters (mm) with a digital caliper.

Forage + seed evaluation

To evaluate the potential for a forage peanut crop to yield both forage and seed, we harvested forage from half of the plots before harvesting the seed crop and compared this with the remaining plots where no forage was harvested during the production of the seed crop. Forage from the dual-purpose plots was harvested from a 1 m^2 area, at 2 cm above ground level on 3 occasions: 30 March (rainy season), 13 June (early dry season) and 19 October 2009 (dry season). Harvested forage was sorted into leaf and stem before drying in a forced-ventilation oven at 65 °C for 72 hours. Response variables measured were: leaf: stem ratio; forage dry mass (FDM); and leaf dry mass (LDM). For statistical analyses, experimental treatments were seed size (small, medium and large) and different harvesting times (rainy, early dry and dry seasons), in a split-plot arrangement, considering seed size as main plots, and presence or absence of harvesting and evaluations along the seasons as subplots. Ground cover values were square-root transformed to satisfy the analysis of variance assumptions.

Seed production was evaluated in October 2009, at the beginning of the rainy season, after the evaluation of forage production in all plots by retrieving seed from the top 10 cm of soil on 1 m^2 of area. Seeds were separated from the soil by hand-sieving followed by washing under running water. Subsequently, they were air-dried by natural ventilation.

Seed quality

Harvested seeds were sorted according to seed size, and their proportions in the total seed lot were determined in the plots that were not subjected to previous harvesting of forage. Limited resources prevented repeating these measurements on seed from plots where forage was harvested before seed harvesting. Seed quality was determined on samples of 300 seeds per treatment based on the emergence test, according to the Seed Testing Guidelines established by Brazilian law (MAPA 2009; 2013) after placing seeds in a forced-ventilation oven at 40 ºC for 14 days (Ferguson 1994) to break dormancy. Seed germination was assessed in trays with sterilized sand, with daily irrigation, under uncontrolled temperature and humidity conditions. Average environmental local temperature and relative humidity of the air during the emergence test were 27 °C and 85%, respectively. Germination rate was determined based on seedling counts at 7, 14 and 28 days after sowing. Additionally, the lengths of seedling shoots and roots were measured (cm) with a graduated scale, 7 days after emergence. The experimental design was a randomized complete block with 4 replications.

Results

Establishment period

There were no significant interactions between seed size and time after sowing on parameters except for ground cover. Pest and disease incidence, plant vigor, flowering intensity and plant height varied significantly with time after sowing (P<0.05) (Table 1), while seed size had significant effects on disease incidence and plant height overall and ground cover at some observations.

Table 1. Effects of seed size and time after sowing on pest and disease incidence, plant vigor, flowering intensity, ground cover and plant height during the establishment period of *Arachis pintoi* cv. BRS Mandobi.

Parameter	Seed size	Weeks after sowing					
		4	8	12	16	20	Mean
Pest incidence	Small	1.50	2.75	1.75	2.75	2.00	2.15
	Medium	2.00	2.75	1.50	2.75	2.00	2.20
	Large	2.50	3.75	2.00	3.00	2.50	2.75
	Mean	2.00	3.08	1.75	2.83	2.17	2.37
Disease incidence	Small	1.00	2.25	3.25	2.25	4.00	2.55 b[1]
	Medium	1.00	2.75	3.25	3.75	3.00	2.75 ab
	Large	1.25	4.00	3.50	3.75	4.00	3.30 a
	Mean	1.08	3.00	3.33	3.25	3.67	2.87
Plant vigor	Small	3.75	4.00	4.50	7.00	9.50	5.75
	Medium	4.50	5.00	5.25	8.00	10.00	6.55
	Large	4.75	5.00	5.50	8.00	10.00	6.65
	Mean	4.33	4.67	5.08	7.67	9.83	6.32
Flowering intensity	Small	0.25	1.00	1.00	2.00	3.25	1.50
	Medium	0.25	1.00	1.00	2.75	2.75	1.55
	Large	0.50	1.00	1.25	2.25	2.00	1.40
	Mean	0.33	1.00	1.08	2.33	2.67	1.48
Ground cover (%)[2]	Small	1.82 a	4.4 a	21.0 b	67.8 b	94.9 a	38.0
	Medium	1.82 a	19.6 a	52.1 a	92.5 a	100.0 a	53.2
	Large	7.29 a	23.7 a	55.1 a	92.5 a	100.0 a	55.7
	Mean	3.6	16.0	42.7	84.2	98.3	36.6
Plant height (cm)	Small	3.25	8.67	13.08	5.08	7.58	7.53 b
	Medium	3.83	8.92	15.33	7.17	11.83	9.42 ab
	Large	4.58	11.25	14.25	8.58	14.75	10.68 a
	Mean	3.89	9.61	14.22	6.94	11.39	9.21

[1]Means within columns followed by the same letter are not significantly different (P>0.05) by Tukey's test. [2]Data analyzed with transformation $x^{(1/2)}$. Pest and disease incidence and flowering: rating scale (0–5); vigor: rating scale (1–10) with higher values indicating higher levels.

Plant vigor and flowering intensity of forage peanut increased with time after sowing, with the coefficient of determination above 90% (Figure 2A). However, pest incidence was constant during the establishment period, so no model was fitted. Disease incidence tended to increase over time, becoming stable towards the end of the study, with coefficient of determination near 90%. Plant height, with coefficient of determination above 70%, showed a cubic model fit, with highest values at the third evaluation. The fitted models were: $-0.24x^2 + 2.01x - 0.47$, $R^2 = 0.90$ for disease; $0.42x^2 - 1.1x + 5.03$, $R^2 = 0.99$ for plant vigor; $0.6x - 0.32$, $R^2 = 0.94$ for flowering intensity; and $1.07x^3 - 10.66x^2 + 32.66x - 19.68$, $R^2 = 0.73$ for plant height.

Ground cover increased linearly during the establishment period, with coefficient of determination above 90% for all seed sizes. The fitted models were: $2.29x - 1.68$, $R^2 = 0.96$ for small seeds; $2.25x - 0.23$, $R^2 = 0.95$ for medium seeds; and $1.94x + 1.12$, $R^2 = 0.96$ for large seeds (Figure 2B).

Leaf morphological characterization

Seed size had significant effects ($P<0.05$) on all leaf morphological characteristics among established plants. Plants originating from small seeds presented smaller morphological characteristics than plants originating from large seeds (Table 2).

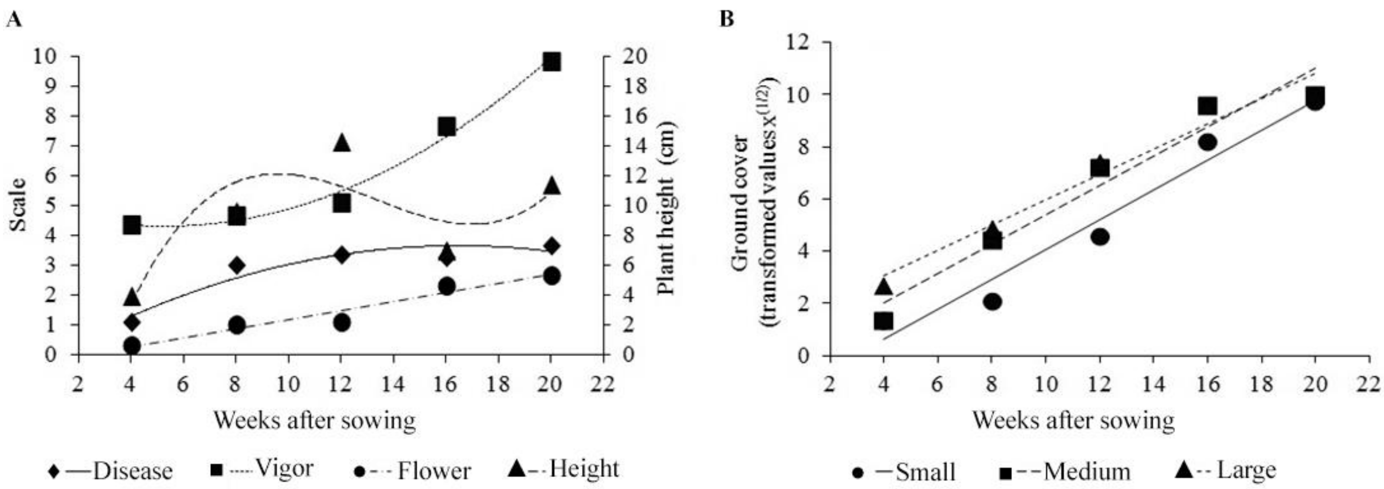

Figure 2. Effects of: **A**) time following sowing on disease incidence, plant vigor, flowering intensity and plant height of *Arachis pintoi* cv. BRS Mandobi (disease incidence and flowering intensity vary on a scale between 0 and 5, and plant vigor varies between 1 and 10); and **B**) time following sowing and seed size on ground cover.

Table 2. Effects of seed size on length and width of basal and apical leaflets and length of petiole of *Arachis pintoi* cv. BRS Mandobi at 120 days after sowing.

Parameter	Treatment	Length (mm)	Width (mm)
Basal leaflet	Small	31.0 b[1]	16.7 b
	Medium	34.1 ab	17.6 ab
	Large	37.5 a	19.2 a
P value		0.011*	0.028*
Apical leaflet	Small	33.8 b	20.3 b
	Medium	37.7 ab	21.3 ab
	Large	42.2 a	23.4 a
P value		0.005**	0.017*
Petiole	Small	39.7 b	
	Medium	44.0 ab	
	Large	47.4 a	
P value		0.022*	

[1]Values within columns and parameters followed by the same letter are not significantly different (P>0.05) by Tukey's test.

Table 3. Effects of seed size and season on total forage (FDM) and leaf (LDM) dry mass production and leaf:stem ratio (L:S) of *Arachis pintoi* cv. BRS Mandobi in pure stands.

Seed size	Season of the year			
	Rainy	Early dry	Dry	
	FDM (kg/ha)			Total
Small	2,663 Bb[1]	3,353 Ba	2,400 Bb	8,416
Medium	3,784 Aa	3,418 Ba	2,579 Bb	9,781
Large	3,729 Aa	4,290 Aa	3,636 Aa	11,655
Mean	3,392	3,687	2,872	9,951
	LDM (kg/ha)			Total
Small	1,695 Ba	1,523 Ba	908 Bb	4,126
Medium	2,451 Aa	1,714 ABb	859 Bc	5,024
Large	2,473 Aa	2,099 Aa	1,353 Ab	5,925
Mean	2,207	1,778	1,040	5,025
	L:S ratio			Mean
Small	1.81	0.88	0.69	1.13
Medium	1.89	1.09	0.59	1.19
Large	2.02	1.01	0.72	1.25
Mean	1.91 a	0.99 b	0.67 c	1.19

[1]Values within columns and parameters followed by the same upper-case letters and within rows followed by the same lower-case letters are not significantly different (P>0.05) by Tukey's test.

Forage + seed evaluation

Total forage dry mass (FDM) and leaf dry mass (LDM) production were significantly affected (P<0.05) by an interaction between seed size and season (Table 3). Stands established with small seeds produced lower amounts of both FDM and LDM than stands established with large seeds, during all seasons (rainy, early dry and dry). On the other hand, differences in FDM and LDM of stands established with small and medium seeds occurred only during the rainy season. Leaf:stem ratio differed only between harvesting seasons, with significant (P<0.05) reductions at successive harvests from the rainy to early dry and dry seasons (Table 3).

Seed production was independent of harvesting management and seed size, with a mean of 2,449 kg/ha. The percentages of small, medium and large seeds produced by plots sown with seeds of different sizes were: 20, 77 and 3% for small; 11, 77 and 12% for medium; and 17, 68 and 15% for large seeds, respectively. However, it was not possible to perform statistical analyses on these data because the seeds belonging to each treatment were mixed, losing individual data for different replicates.

Seed germination rate and seedling vigor

There was no significant (P>0.05) effect of seed size on seed germination rate and seedling vigor, based on lengths of the shoots and roots at 7 days after emergence. The mean lengths of shoots of seedlings originating from small, medium and large seeds were 9.79, 10.16 and 10.25 cm, and the mean lengths of roots were 5.50, 5.27 and 6.04 cm, respectively. Seed size at planting did not affect viability of seed produced (P>0.05), with germination percentages of 13.7, 16.6 and 18.1% for seed originating from small, medium and large seeds, respectively.

Discussion

The failure of harvesting management to affect seed production of *A. pintoi* was an important finding as it justifies harvesting forage from a seed crop prior to collecting seed. This would provide an additional source of high quality forage to supplement livestock in periods with restriction of forage supply (Ladeira et al. 2002; Awad et al. 2013) or an additional source of income through sale of the forage.

Brum et al. (2009) and Demétrio et al. (2012) suggest that management practices can increase biomass production of forage species, especially legumes in intercropping systems with two or more harvests, by promoting the appearance of new shoots, which results in higher regrowth rates. In contrast, production of seeds and grains may decrease, mainly because regrowth interval after the final harvest is too short to allow for complete seed development. Therefore, forage + seed production systems require different management strategies for production of seed and forage simultaneously for most species (Bortolini et al. 2004; Dávila et al. 2011). This is particularly important in the case of forage peanut BRS Mandobi, which has a cycle of 128 days between flower setting and seed maturity. Additionally, depending on the *A. pintoi* genotype, seed production may be influenced by crop management strategies, mainly related to harvest intensity and frequency (Argel 1994; Ferguson 1994; Dávila et al. 2011). It was interesting that forage harvesting times we chose varied from March to October, but there was no effect on the seed yields obtained.

The fact that plants established with large seeds had higher incidence of diseases is possibly due to their taller and more closed canopy conditions, providing favorable environmental conditions for survival and multiplication of plant pathogens, with higher humidity between the canopy and the soil and dead organic matter from crop residues (Assis et al. 2011). Increases in plant height during the early part of the establishment period were expected as plants were growing rapidly, while the declines after 12 weeks resulted from partial lodging due to increase in size and mass.

As all treatments had similar plant numbers, different seed sizes resulted in different seeding rates (kg/ha), which may have resulted in the lower ground cover observed during the establishment when small seeds were sown. If the same seeding rates had been employed for all treatments, this would have resulted in higher plant densities in treatments with medium and small seeds and areas established with these seeds would be expected to achieve higher levels of ground cover in the same period after planting than areas planted with large seeds. Since seed size did not affect ground cover at the end of the establishment period, around 120 days after sowing, this suggests that the lower seeding rates employed with smaller seed could be quite satisfactory. However, even with satisfactory ground cover and plant vigor at the end of the establishment period, the production of forage in areas established with small seeds was lower during all seasons, when compared with areas established with large seeds.

The smaller leaves on plants originating from small seeds had a negative effect on initial speed of plant growth and establishment of ground cover and increased the opportunity for emergence of weeds that compete directly for light, water and nutrients. Larger leaves tend to have higher energy expenditure for growth than smaller leaves, thus demanding greater availability of resources, such as light and nutrients (Milla and Reich 2007). Even though the use of smaller seeds for crop establishment may result in plants with smaller leaves, the adjustment of seeding rate with higher plant densities could compensate for this initial disadvantage (Andrade et al. 1997).

The failure of seed size to affect leaf:stem ratio showed that leaf emission is independent of seed size, but greatly affected by climatic conditions. During the approximately 100-day regrowth period evaluated in the dry season, leaf mass was 50% lower than during the rainy season, while total forage mass was only 15% lower, indicating greater presence of stem tissue. This pattern of crop growth is a response to climate variation during the year. Leaf:stem ratio is important in studies with forage species, since it directly affects sunlight interception and plant metabolism, thus influencing seed and forage production. It also affects liveweight gain of grazing animals, because higher leaf percentage improves pasture nutritive value and increases digestibility and forage dry matter intake (Rocha et al. 2007; Ribeiro et al. 2012; Awad et al. 2013).

While there is a dearth of information regarding the inheritance and mode of action of seed size in *A. pintoi* in the literature, *A. hypogaea* shows high heritability for seed size, with potential for indirect selection for multiple characters positively and negatively related with this trait (Kotzamanidis et al. 2006; Sikinarum et al. 2007). This has been observed for grain species, suggesting the action of a low number of genes with additive effects, which allows selection for this character in the first segregating generations (Lopes et al. 2003; Hakim et al. 2014). The results of our study showed that size of seeds at planting had little effect on sizes of seeds produced. However, there was some variation, which may have genetic and/or micro-environmental causes. While the proportion of variation resulting from each of these effects could not be determined in this study, other studies with forage peanut have shown that there is intra-cultivar variation for BRS Mandobi. Assis et al. (2016) demonstrated that there is genetic variation for seed size within BRS Mandobi by evaluating individual plants. Later, Azevedo (2017) confirmed the existence of genetic variability between progenies selected from individual plants of BRS Mandobi, and estimated average heritability for weight of 100 seeds of 0.89. However, additional studies are needed to better understand the mechanisms of seed size inheritance in *A. pintoi*.

Quality of seed produced was not affected by seed size at planting, although Beckert et al. (2000) and Perin et al. (2002) suggested that larger seeds tend to produce more developed and vigorous seedlings. According to Bredemeier et al. (2001), the ability of large seeds to produce larger seedlings than small seeds is more pronounced under stress conditions and in early stages of seedling development, and this effect tends to disappear by the end of the establishment period, with no effect on the resulting seed yield. We observed a similar phenomenon in this study among areas of *A. pintoi* planted with different seed sizes, which showed no differences in ground cover at the end of the establishment period, leaf:stem ratio and seed production and quality. As seed size did not influence germination rate, using a standard planting rate would result in sowing 61% more small seeds per unit area than with medium seeds, resulting in higher planting densities, thus speeding the establishment process and reducing weeding costs. Alternatively using lower sowing rates with small and medium seeds would reduce seed costs, while achieving similar planting densities as compared with the use of large seeds. This is an important consideration because availability of seeds in the world market is low and the unit cost is very high (around US$ 40/kg), which limits wider adoption of this technology.

Germination rates below 20% obtained in the present study were due to the seed dormancy mechanism present in *A. pintoi*, which possibly has both physiological and physical components (Ferguson 1994; Assis et al. 2015). Although low germination rates were obtained, they were not related to seed size from which the plant originated and appropriate adjustments in the seed dormancy-breaking method would most likely result in substantially higher seed germination rates. We tested the ungerminated seeds from the germination tests using tetrazolium and verified that viability of all seed size lots was the same ($P>0.05$), with an average of 90.3%.

Forage + seed production systems are of great interest, because they enable farmers to diversify and increase their sources of income with the production of high quality forage, while maintaining their capacity to produce seeds from the same area. In fact, similar systems are common in Southern Brazil, mainly for production of grain as well as forage for feeding animals, especially during the dry season (Fontaneli et al. 2009; Meinerz et al. 2012). Forage + seed production systems are recommended in tropical and semi-arid regions of Central and South American countries, Southern Africa, Asia and Australia (Peters et al. 2001; Whitbread and Pengelly 2004). These systems can also become a viable alternative for high quality forage and seed production in tropical areas with adequate environmental conditions for growth and persistence of *A. pintoi*. The dry matter yields of forage would present a significant resource for sale or use as forage on the farm, and should either increase returns or enable seed to be marketed at a cheaper price.

Conclusions

While seed size at planting had no effect on most parameters, including seed yield in a mono-specific pasture, these findings might not relate to results from a grass-legume pasture where competition from the grass might be strong. The lower initial crop establishment and forage mass in areas cultivated with small seeds support this possibility. Further studies on the effects of different seed sizes and seeding rates on forage peanut establishment and forage production in mixed stands seem warranted to determine if seed number and not seeding rate/ha is the critical factor in establishment.

Harvesting of forage as a by-product during the growth cycle prior to harvesting seed seems not to affect seed yields, so this strategy could be a mechanism to offset the high costs of seed production in *A. pintoi.*

Results from this study have failed to provide conclusive evidence whether variation in seed size of BRS Mandobi is mainly genetic or a response to micro-environmental conditions. Further studies with individual plants are necessary to attempt to clarify the factors relating to heritability of seed size.

Acknowledgments

This research was supported financially by Brazilian Agricultural Research Corporation (Embrapa). We also thank Council for Scientific and Technological Development (CNPq) for the scholarship granted to the first author and National Council for the Improvement of Higher Education (CAPES) for the scholarships granted to the second and third authors.

References

(Note of the editors: All hyperlinks were verified 3 September 2018.)

Abreu A de Q; Andrade CMS; Farinatti LHE; Nascimento HLB do. 2012. Taxa de semeadura de *Arachis pintoi* cv. Mandobi para formação de pastos consorciados. Anais da XLIX Reunião Anual da Sociedade Brasileira de Zootecnia, Brasília, DF, Brazil, 23–24 July 2012. goo.gl/ZVtznB

Andrade RV de; Andreoli C; Borba C da S; Azevedo JT de; Netto DAM; Oliveira AC de. 1997. Efeito da forma e do tamanho da semente no desempenho no campo de dois genótipos de milho. Revista Brasileira de Sementes 19:62–65. goo.gl/5oEjRh

Argel PJ. 1994. Regional experience with forage *Arachis* in Central America and Mexico. In: Kerridge PC; Hardy B, eds. Biology and agronomy of forage *Arachis*. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p. 132–143. hdl.handle.net/10568/54359

Assis GML de; Valentim JF; Andrade CMS de. 2011. Produção de sementes de *Arachis pintoi* cv. BRS Mandobi no Acre. Sistema de Produção Embrapa 4, Rio Branco, AC, Brazil. goo.gl/NPmRX3

Assis GML de; Valentim JF. 2013. Forage peanut breeding program in Brazil. In: Jank L; Chiari L; Valle CB do; Resende RMS, eds. Forage breeding and biotechnology. Embrapa Gado de Corte, Campo Grande, MS, Brazil. p. 77–105. goo.gl/ttYDJF

Assis GML de; Valentim JF; Andrade CMS de. 2013. BRS Mandobi: A new forage peanut cultivar propagated by seeds for the tropics. Tropical Grasslands-Forrajes Tropicales 1:39–41. DOI: 10.17138/tgft(1)39-41

Assis GML de; Kryzanowski FC; Azevedo HN de. 2015. Superação de dormência em sementes de amendoim forrageiro cv. BRS Mandobi. Circular Técnica 70. Embrapa Acre, Rio Branco, AC, Brazil. goo.gl/RxQmzD

Assis GML de; Miqueloni DP; Clemencio R de M; Azevedo HN de. 2016. Seleção massal em amendoim forrageiro com foco no vigor de plantas, tamanho e produtividade de sementes. Anais de XXVI Congresso Brasileiro de Zootecnia, Santa Maria, RS, Brazil, 11–13 May 2016. goo.gl/ZmLwWQ

Awad A; Hafiz S; Hammada MS; El-Nouby A; El-Hendawy S. 2013. Grain yield production of Sudan grass [*Sorghum sudanense* (Piper) Stapf] as influenced by cutting numbers, potassium rates, and intrarow spacing in a semiarid environment. Turkish Journal of Agriculture and Forestry 37:657–664. goo.gl/RpJUcS

Azevedo HN de. 2017. Estimação de parâmetros genéticos em progênies de amendoim forrageiro. M.Sc. Thesis. Universidade Federal do Acre, Rio Branco, AC, Brazil. goo.gl/4FmszT

Beckert OP; Miguel MH; Marcos Filho J. 2000. Absorção de água e potencial fisiológico em sementes de soja de diferentes tamanhos. Scientia Agricola 57:671–675. DOI: 10.1590/S0103-90162000000400012

Bortolini PC; Sandini I.; Carvalho PCF; Moraes A de. 2004. Cereais de inverno submetidos ao corte no sistema de duplo propósito. Revista Brasileira de Zootecnia 33:45–50. DOI: 10.1590/S1516-35982004000100007

Bredemeier C; Mundsock CM; Buttenbender D. 2001. Efeito do tamanho das sementes de trigo no desenvolvimento inicial das plantas e no rendimento de grãos. Pesquisa Agropecuária Brasileira 36:1061–1068. DOI: 10.1590/S0100-204X2001000800008

Brum OB; López S; García R; Andrés S; Calleja A. 2009. Influence of harvest season, cutting frequency and nitrogen fertilization of mountain meadows on yield, floristic composition and protein content of herbage. Revista Brasileira de Zootecnia 38:596–604. DOI: 10.1590/S1516-35982009000400002

Dávila C; Urbano D; Castro F. 2011. Efecto de la altura y frecuencia de corte sobre tres variedades de maní forrajero (*Arachis pintoi*) en el estado Mérida II. Características morfológicas y producción de semilla. Zootecnia Tropical 29:7–15. goo.gl/M9QTQG

Demétrio JV; Costa ACT da; Oliveira PSR de. 2012. Produção de biomassa de cultivares de aveia sob diferentes manejos de corte. Pesquisa Agropecuária Tropical 42:198–205. DOI: 10.1590/S1983-40632012000200011

Ferguson JE. 1994. Seed biology and seed systems for *Arachis pintoi*. In: Kerridge PC; Hardy B, eds. 1994. Biology and agronomy of forage *Arachis*. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p. 122–133. hdl.handle.net/10568/54359

Ferreira DF. 2014. Sisvar: A guide for its bootstrap procedures in multiple comparisons. Ciência e Agrotecnologia 38:109–112. DOI: 10.1590/S1413-70542014000200001

Fontaneli RS; Fontaneli RS; Santos HP dos; Nascimento Junior A do; Minella E; Caieirão E. 2009. Rendimento e valor nutritivo de cereais de inverno de duplo propósito: forragem verde e silagem ou grãos. Revista Brasileira de Zootecnia 38:2116–2120. DOI: 10.1590/S1516-35982009001100007

Hakim L; Suyamto S; Paturohman E. 2014. Genetic variability and expected genetic advances of quantitative characters in F2 progenies of soybean crosses. Indonesian Journal of Agricultural Science 15:11–16. DOI: 10.21082/ijas.v15n1.2014.p11-16

INMET (Instituto Nacional de Meteorologia). 2015. BDMEP - Banco de Dados Meteorológicos para Ensino e Pesquisa. goo.gl/pMRBq8

Kotzamanidis ST; Stavropoulus N; Ipsilandis CG. 2006. Correlation studies of 21 traits in F2 generation of groundnut (*Arachis hypogaea* L.). Pakistan Journal of Biological Sciences 9:929–934. DOI: 10.3923/pjbs.2006.929.934

Ladeira MM; Rodriguez NM; Borges I; Gonçalves LC; Salibra E de OS; Brito SC; Sá LAP de. 2002. Avaliação do feno de *Arachis pintoi* utilizando o ensaio de digestibilidade *in vivo*. Revista Brasileira de Zootecnia 31:2350–2356. DOI: 10.1590/S1516-35982002000900025

Lopes FC da C; Gomes RLF; Freire Filho FR. 2003. Genetic control of cowpea seed sizes. Scientia Agricola 60:315–318. DOI: 10.1590/S0103-90162003000200016

MAPA (Ministério da Agricultura, Pecuária e Abastecimento). 2009. Regras para análise de sementes. MAPA/ACS, Brasília, DF, Brazil. goo.gl/nwXUUE

MAPA (Ministério da Agricultura, Pecuária e Abastecimento). 2013. Instrução Normativa No. 41, de 11 de Setembro de 2013. Diário Oficial da União 178, Brasília, DF, Brazil. goo.gl/R1Q1pP

Meinerz GR; Olivo CJ; Fontaneli RS; Agnolin CA; Horst T; Bem CM de. 2012. Produtividade de cereais de inverno de duplo propósito na depressão central do Rio Grande do Sul. Revista Brasileira de Zootecnia 41:873–882. DOI: 10.1590/S1516-35982012000400007

Milla R; Reich PB. 2007. The scaling of leaf area and mass: The cost of light interception increases with leaf size. Proceedings of the Royal Society B 274:2109–2115. DOI: 10.1098/rspb.2007.0417

Perin A; Araújo AP; Teixeira MG. 2002. Efeito do tamanho da semente na acumulação de biomassa e nutrientes e na produtividade do feijoeiro. Pesquisa Agropecuária Brasileira 37:1711–1718. DOI: 10.1590/S0100-204X2002001200006

Peters M; Horne P; Schmidt A; Holmann F; Kerridge PC; Tarawali SA; Schultze-Kraft R; Lascano CE; Argel P; Stür W; Fujisaka S; Müller-Sämann K; Wortmann C. 2001. The role of forages in reducing poverty and degradation of natural resources in tropical production systems. Agricultural Research and Extension Network Paper, No. 117. Overseas Development Institute (ODI), London, UK. goo.gl/1xePY1

Ramos AKB; Barcellos AO; Fernandes FD. 2010. Gênero *Arachis*. In: Fonseca DM; Martuscello JA, eds. Plantas forrageiras. Editora UFV, Viçosa, MG, Brazil. p. 250–293.

Ribeiro OL; Cecato U; Rodrigues AM; Faveri JC; Santos GT dos; Lugão SMB; Beloni T. 2012. Composição botânica e química da Coastcross consorciada ou não com *Arachis pintoi*, com e sem nitrogênio. Revista Brasileira de Saúde e Produção Animal 13:47–61. DOI: 10.1590/S1519-99402012000100005

Rocha MG da; Quadros FLF de; Glienke CL; Confortin ACC; Costa VG da; Rossi GE. 2007. Avaliação de espécies forrageiras de inverno na Depressão Central do Rio Grande do Sul. Revista Brasileira de Zootecnia 36:1990–1999. DOI: 10.1590/S1516-35982007000900007

Shelton HM; Franzel S; Peters M. 2005. Adoption of tropical legume technology around the world: Analysis of success. Tropical Grasslands 39:198–209. https://goo.gl/GwRMN1

Sikinarum J; Jaisil P; Jogloy S; Toomsan B; Kesmala T; Patanothai A. 2007. Heritability and correlation for nitrogen (N_2) fixation and related traits in peanut (*Arachis hypogaea* L.). Pakistan Journal of Biological Sciences 10:1956–1962. DOI: 10.3923/pjbs.2007.1956.1962

Whitbread AM; Pengelly BC, eds. 2004. Tropical legumes for sustainable farming systems in southern Africa and Australia. ACIAR Proceedings No. 115. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. goo.gl/vqbvcG

(Received for publication 28 September 2017; accepted 25 June 2018; published 30 September 2018)

DOI: 10.17138/TGFT(6)158-168

Artículo Científico

Efectos de la fertilización en la productividad de una pastura de *Brachiaria humidicola* cv. Llanero en el Piedemonte de los Llanos Orientales de Colombia

Effects of fertilization of Brachiaria humidicola *cv. Llanero on pasture productivity in the foothills region of the Llanos Orientales, Colombia*

ÁLVARO RINCÓN[1], HERNANDO FLÓREZ[1], HUGO BALLESTEROS[2] Y LEANDRO M. LEÓN[1]

[1]*Red de Ganadería y Especies Menores, Corporación Colombiana de Investigación Agropecuaria (Agrosavia), C.I. La Libertad, Villavicencio, Meta, Colombia.* www.agrosavia.co
[2]*Oficina de Desarrollo de Negocios, Corporación Colombiana de Investigación Agropecuaria (Agrosavia), C.I. La Libertad, Villavicencio, Meta, Colombia.* www.agrosavia.co

Resumen

En una pastura de *Brachiaria humidicola* cv. Llanero no degradada, manejada con una fertilización de mantenimiento bianual durante 15 años, ubicada en un Oxisol ácido y de baja fertilidad en el Piedemonte llanero de Colombia, se evaluaron 3 tratamientos de fertilización: T1 - sin fertilización (testigo); T2 - fertilización básica (kg/ha: P 20, Ca 18, Mg 20, K 18, S 31 y N 18); y T3 - fertilización básica+urea (kg/ha: P 20, Ca 18, Mg 20, K 18, S 31 y N 110). Cada tratamiento estuvo compuesto por 4 potreros de 0.8 ha cada uno donde pastaron en forma secuencial grupos de toretes Cebú Brahman, con un período de ocupación de 7 días y un período de descanso de 21 días. Tanto en época lluviosa como seca la producción de forraje durante cada descanso fue más alta en T3 (1,540 y 940 kg MS/ha, respectivamente) que en T2 (979 y 665 kg MS/ha) y T1 (958 y 613 kg MS/ha). La fertilización básica+urea también aumentó la concentración de PC en el forraje en época lluviosa (9.9%, en comparación con 8.4 y 8.1% en T2 y T1, respectivamente). En 250 días de pastoreo del experimento, incluyendo 173 días de época lluviosa y 77 días de época seca, la producción de peso vivo por hectárea fue de 317, 599 y 870 kg/ha para T1, T2 y T3, respectivamente, con cargas animal de 2.2, 3.0 y 3.8 unidades animal/ha (1 UA = 400 kg peso vivo) en la época lluviosa, y 1.6, 2.1 y 3.2 UA/ha en la época seca, respectivamente. Las ganancias de peso vivo por animal y día fueron, en el mismo orden, 589, 782 y 878 g/an/día en la época lluviosa y 379, 642 y 721 g/an/día en la época seca. En términos económicos, T3 (fertilización básica+urea) representó un ingreso neto adicional de US$ 658/ha respecto al testigo y de US$ 349 respecto a T2. Mientras que el estudio presenta evidencia del potencial de la fertilización, sobre todo nitrogenada, de pasturas de *B. humidicola* cv. Llanero para la intensificación de la producción ganadera en la región, se requieren experimentos a largo plazo para confirmar la sostenibilidad de estos sistemas.

Palabras clave: Carga animal, ganancia de peso vivo, nitrógeno, producción de forraje, rentabilidad, valor nutritivo.

Abstract

In the foothills region of the Llanos Orientales, Colombia the effects of 3 fertilizer treatments, based on regionally available fertilizers: T1 - no fertilizer (control); T2 - basic fertilizer (kg/ha: P 20, Ca 18, Mg 20, K 18, S 31 and N 18); and T3 - basic fertilizer + additional urea (kg/ha: P 20, Ca 18, Mg 20, K 18, S 31 and N 110), were studied on a non-degraded *Brachiaria humidicola* cv. Llanero pasture located on an acid, infertile Oxisol that had received biannual maintenance fertilizer for 15 years. Each treatment was composed of 4 paddocks of 0.8 ha each, which were rotationally

Correspondencia: Álvaro Rincón C., Agrosavia, C.I. La Libertad, km 17 vía a Puerto López, Meta, Colombia.
Correo electrónico: arincon@agrosavia.co

grazed (7 days grazing and 21 days rest) by a group of Brahman Cebu bulls. Forage production during the rest periods was higher in T3 in both the rainy and dry seasons (1,540 and 940 kg DM/ha, respectively) than in T2 (979 and 665 kg DM/ha) and T1 (958 and 613 kg MS/ha). In T3 also CP concentration in rainy season forage was higher (9.9%) than in T2 and T1 (8.4 and 8.1%, respectively). After a total of 250 days of grazing during the rainy (173 days) and dry seasons (77 days), liveweight production was 317, 599 and 870 kg/ha for T1, T2 and T3, respectively, with stocking rates of 2.2, 3.0 and 3.8 animal units/ha (1 AU = 400 kg live weight) in the rainy and 1.6, 2.1 and 3.2 AU/ha in the dry season, respectively. Daily liveweight gains were, in the same order, 589, 782 and 878 g/animal/day in the rainy season and 379, 642 and 721 g/an/day in the dry season. In economic terms, T3 (basic fertilizer plus urea) represented an additional net income of $US 658/ha in comparison with the control treatment and $US 349/ha in comparison with T2. While the study provides evidence that fertilizing of pasture, particularly with N, has potential to contribute to intensification of livestock production in the region, long-term experiments are required to confirm the sustainability of such systems.

Keywords: Forage production, liveweight gains, nitrogen, nutritive value, profitability, stocking rate.

Introducción

El pasto *Brachiaria humidicola* cv. Llanero (antes conocido como *B. dictyoneura*) es una gramínea adaptada a suelos ácidos de baja y mediana fertilidad y alta saturación de aluminio, predominantes en la Orinoquia (Llanos Orientales) de Colombia. Fue entregado a los productores hace cerca de 30 años en Colombia (ICA 1987) y sigue siendo una de las mejores alternativas para los sistemas ganaderos de la región. Por su hábito de crecimiento postrado e invasor forma un tapete denso que protege el suelo de la erosión y compactación por pisoteo del ganado. El pasto Llanero se ha establecido con éxito en suelos arenosos y arcillosos de la Orinoquia, preferiblemente en suelos bien drenados; sin embargo, también crece bien en suelos con saturación temporal de agua. El sobrepastoreo y la baja fertilidad de los suelos en la región traen como consecuencia la degradación de las pasturas (Rincón 2006), lo cual sumado a la falta tradicional de fertilización de mantenimiento de los pastos, incluyendo el cv. Llanero, resulta en ganancias de peso vivo animal menores a 400 g/an/día, con una capacidad de carga inferior de 2 UA/ha (1 UA = 400 kg de peso vivo). El pasto Llanero es de amplia difusión en la región – estimamos que en la Orinoquia colombiana existe actualmente cerca de 1 millón de hectáreas sembradas con esta gramínea – pero igual a la mayoría de los pastos introducidos en la región está en peligro de degradación severa como consecuencia de prácticas de manejo no adecuadas (Rincón 2011).

Además del nitrógeno (N), para el establecimiento y producción de pasturas en el Piedemonte de los Llanos Orientales de Colombia es necesario aplicar, entre otros nutrientes: fósforo (P), calcio (Ca), potasio (K), magnesio (Mg) y azufre (S). El N participa en la actividad fotosintética de la planta, en la movilización de reservas en la planta, en la expansión del área foliar y en la producción de rebrotes (Salisbury y Ross 1992; Martha Júnior et al. 2004). Además es un constituyente básico para la síntesis de proteínas, que conjuntamente con la energía metabolizable son los principales factores que afectan la degradación del forraje en el rumen (MLA 2006; CSIRO 2007). Minson (1973) reportó un incremento en la digestibilidad de la MS en 2.2% y de la materia orgánica en 1.3% de pastos fertilizados con N. Johnson et al. (2001) encontraron que la fertilización nitrogenada redujo la fibra en detergente neutro (FDN) e incrementó la concentración total de N y la digestibilidad in vitro de la materia orgánica en pastos tropicales. Peyraud y Astigarraga (1998) encontraron que la fertilización nitrogenada aumenta levemente la energía neta y la proteína metabolizable lo que impacta positivamente los nutrientes digestibles totales y el valor energético del forraje.

Teniendo en cuenta las deficiencias que existen actualmente para la adecuada alimentación de bovinos en el Piedemonte llanero, la presente investigación tuvo como objetivo: (1) medir el efecto de la aplicación de fertilizantes disponibles en el mercado en una pastura establecida del cv. Llanero, sobre la producción y la calidad del forraje, la capacidad de carga animal y la ganancia de peso vivo; y (2) analizar la viabilidad económica de esta práctica.

Materiales y Métodos

Localización

El experimento se realizó entre junio 17 de 2015 y marzo 3 de 2016 en el Centro de Investigaciones La Libertad de la Corporación de Investigación Agropecuaria de Colombia (Corpoica; ahora: Agrosavia), localizado a 17 km de la ciudad de Villavicencio, Meta, Colombia, a 4º03' N y 73º28' O, a 300 msnm de altitud y en condiciones de clima y suelo representativas del Piedemonte llanero.

Clima

La temperatura promedio es de 26 °C, la precipitación anual de 2,953 mm y la humedad relativa de 80%. La época de lluvias comienza a finales de marzo y termina a mediados de diciembre. No obstante, en los meses secos entre enero y marzo se presentan lluvias ocasionales que pueden llegar a 114 mm, valor superior a los 28 mm obtenidos en los mismos meses del año 2016, cuando se realizó el presente trabajo (Figura 1). Históricamente (30 años) el mes más lluvioso ha sido mayo con un promedio de 445 mm; sin embargo, en abril de 2015 se presentó la máxima precipitación (521 mm), siendo atípica para la región.

Suelo

El sitio experimental es caracterizado por una topografía plana y homogénea, con un suelo Oxisol franco-arcillo-arenoso bien drenado, caracterizado por alta acidez, toxicidad de aluminio (Al), baja disponibilidad de P, baja capacidad de intercambio catiónico y deficiencias en la mayoría de los nutrientes esenciales para las plantas (Ayarza 1991). El análisis de suelo antes del comienzo del experimento arrojó los resultados siguientes: pH 4.8; materia orgánica 2.9%; P (Bray II) 1.5 mg/kg; S 2.9 mg/kg; Ca 0.7 cmol/kg; Mg 0.10 cmol/kg; y K 0.08 cmol/kg. Estas concentraciones son inferiores a los requerimientos señalados por Salinas y García (1985) y Ayarza (1991) para pastos en suelos ácidos: P 10 mg/kg; S 15 mg/kg; Ca 1.0 cmol/kg; Mg 0.20 cmol/kg; y K 0.10 cmol/kg.

Tratamientos

Para el estudio se utilizó un área total de 9.6 ha en una pastura de *Brachiaria humidicola* cv. Llanero utilizada previamente durante 15 años para ceba de ganado en un sistema de pastoreo alterno con 30 días de ocupación e igual número de días de descanso. Al comienzo del ensayo la pastura se encontraba en buen estado (cobertura del suelo >90%). Cada 2 años recibía una aplicación (kg/ha) de 20 P, 46 N y 25 K como fertilización de mantenimiento; la última aplicación fue l año anterior a la iniciación de este estudio. El área total fue dividida en parcelas de 3.2 ha para la aplicación de los tratamientos siguientes:

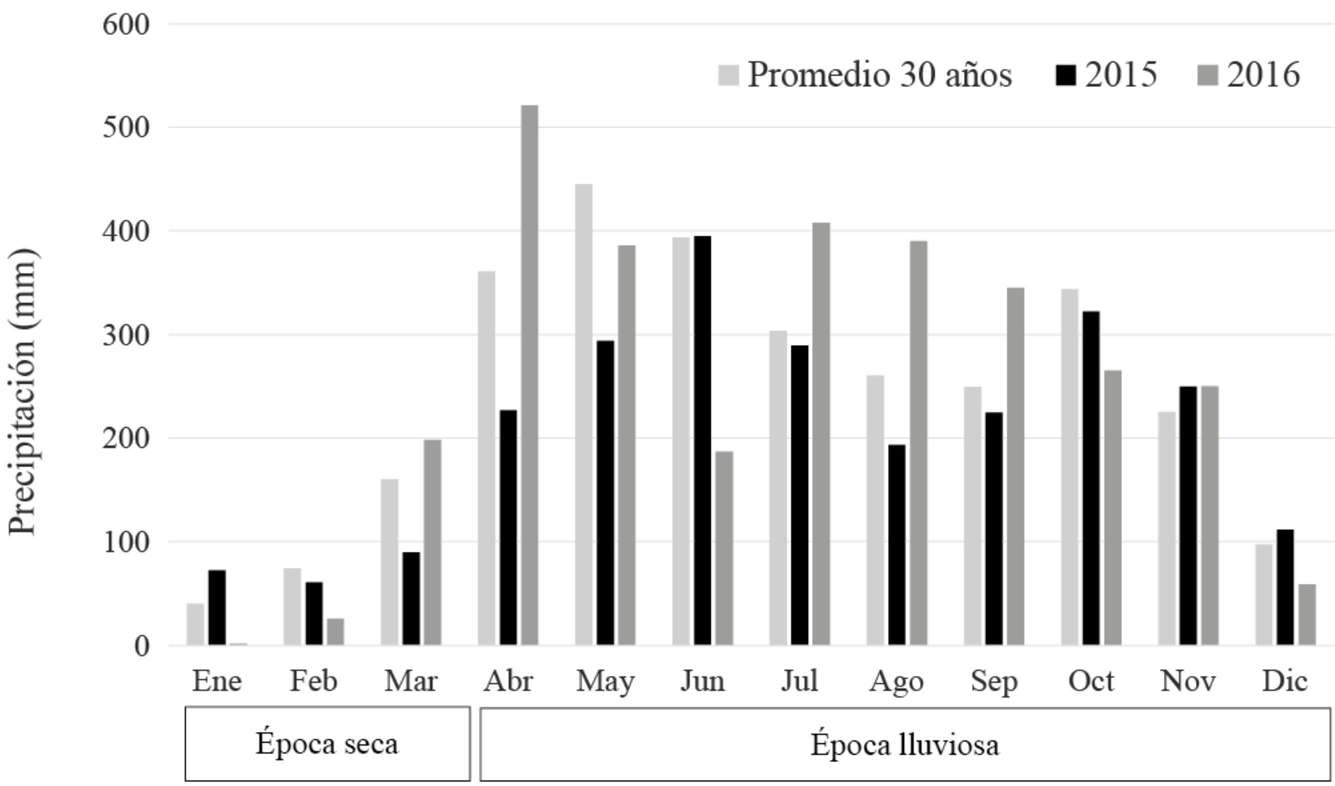

Figura 1. Precipitación en 2015 y 2016 comparada con el promedio de 30 años. C.I. La Libertad, Villavicencio, Colombia.

T1: Testigo sin fertilización.

T2: Fertilización básica (kg/ha): 20 P, 18 Ca, 20 Mg, 18 K, 31 S, 18 N (DAP-N).

T3: Fertilización básica+urea: (kg/ha): 20 P, 18 Ca, 20 Mg, 18 K, 31 S, 110 N (18 DAP-N, 92 urea-N).

Cada tratamiento consistió en 4 parcelas de 0.8 ha cada una, separadas con cerca eléctrica, que fueron utilizadas en pastoreo rotacional (7 días de ocupación, 21 días de descanso) con su grupo de animales correspondiente.

Las dosis de fertilizantes aplicadas fueron seleccionadas de acuerdo con los análisis de suelo y las recomendaciones de Ayarza (1991) para pastos en la región. Como fuentes de nutrientes se utilizaron fertilizantes disponibles en el mercado: fosfato diamónico (DAP) como fuente de P (20%) y N (18%); sulpomag como fuente de S (22%), K (18%) y Mg (11%); sulcamag como fuente de Ca (18%), Mg (9%) y K (9%); y urea como fuente de N (46%). La dosis de N en T3 fue seleccionada con base en los trabajos de Rincón y Ligarreto (2011) y Rincón (2012). El N adicional en este tratamiento fue aplicado en forma de urea fraccionado en 50% en el momento de la aplicación de la fertilización básica (julio de 2015) y 50% 3 meses más tarde, en octubre de 2015. Los fertilizantes fueron mezclados y aplicados al voleo en forma manual en el mes de julio, 15 días después de iniciado el pastoreo, coincidiendo con la reducción de las lluvias para evitar pérdidas de nutrientes por escorrentía.

Manejo del pastoreo

La ganancia de peso animal en cada tratamiento se determinó utilizando 3 grupos de toretes Cebú Brahman. La carga animal inicial se asignó con base en la disponibilidad de forraje después de un período de descanso de 21 días (800, 1,100 y 1,400 kg MS/ha en T1, T2 y T3, respectivamente) y asumiendo una presión de pastoreo de 4 kg MS/100 kg de peso vivo animal. Como resultado, las cargas iniciales fueron de 2.2, 3.0 y 3.8 unidades animal (UA)/ha equivalentes a 8, 11 y 14 animales de 350 kg, para los Tratamientos 1, 2 y 3, respectivamente. En cada tratamiento los animales fueron manejados en un sistema de rotación en los 4 potreros de cada tratamiento, con 7 días de ocupación y 21 días de descanso (7/21) con un peso, promedio, inicial de 350 kg y edades de 2 a 2.3 años hasta alcanzar un peso final de 520 kg. Se suministró sal mineralizada (6% de P) a voluntad y se realizaron los controles sanitarios como vacunaciones, vermifugaciones y baños garrapaticidas, de acuerdo con los cronogramas de la región. Durante la época lluviosa de 2015 los animales estuvieron en pastoreo durante 173 días de época lluviosa (junio 17 hasta diciembre 9 de 2015) y 77 días de época seca (diciembre 13 de 2015 hasta marzo 3 de 2016), para un total de 250 días de evaluación. Al inicio de la época seca se ajustó la carga, reduciendo el número a la mitad en cada tratamiento.

Diseño experimental

Para los tratamientos de fertilización del pasto, el diseño experimental fue de bloques completos al azar con 4 repeticiones. Respecto a la producción de peso vivo animal, el diseño experimental fue de tipo continuo donde los animales permanecieron pastoreando en las áreas correspondientes a su tratamiento; cada animal fue considerado como una repetición (Amézquita 1986).

Evaluaciones

Producción de forraje. La producción de forraje fue determinada mediante la toma de 2 muestras en época lluviosa (agosto y octubre de 2015) y una en época seca (febrero de 2016), utilizando metodología convencional, en transectos con 20 observaciones en cada potrero, con un marco de 0.50 x 0.50 m. Estos muestreos se realizaron en forma secuencial en cada potrero al finalizar el período de descanso y antes de entrar los animales al pastoreo. Además se estimó en forma visual el porcentaje de cobertura del suelo en cada sitio muestreado, como indicador de un manejo de pastoreo adecuado que evite compactación y erosión del suelo.

Calidad nutritiva del forraje. En octubre de 2015 (época de lluvias) se tomaron muestras del forraje cosechado en las evaluaciones de producción para determinar la concentración de proteína cruda (PC) por micro-Kjeldahl (AOAC 1995); fibra en detergente ácido (FDA) (Van Soest 1963); fibra en detergente neutro (FDN) (Van Soest y Wine 1967); y degradabilidad in situ de la materia seca en bolsa de nylon utilizando un bovino Cebú comercial de 680 kg fistulado en el rumen que pastoreaba en una pradera de *B. decumbens* con acceso a sal mineralizada y agua a voluntad. Las bolsas con las muestras (5 g) se incubaron en el rumen por triplicado por espacio de 48 horas; luego se extrajeron y el residuo se analizó siguiendo los métodos descritos por Nocek y English (1986).

Aporte de nutrientes de la ración. Con el fin de conocer el aporte de nutrientes y el valor energético del forraje en oferta de cada tratamiento, se utilizó el software Large Ruminant Nutrition System (LRNS) de la Universidad de Texas (nutritionmodels.com/lrns.html) el cual permite estimar los requerimientos y el suministro de nutrientes a ganado de carne y/o leche mediante modelos de función ruminal, tasas de pasaje del alimento, digestibilidad y crecimiento, teniendo en cuenta el tipo de animal, los factores climáticos, el manejo y la composición nutricional del alimento. El programa utiliza el motor computacional del modelo Cornell Net Carbohydrate and Protein System (CNCPS) desarrollado por Fox et al. (2004) y validado en condiciones tropicales (Parsons et al. 2011).

Ganancia de peso vivo. Los animales se pesaron cada 30 días utilizando una báscula Tru-Test EC 2000 (Tru-Test Ltd, Auckland, Nueva Zelanda). En total se reali-zaron 3 pesajes en la época lluviosa (agosto 11, octubre 23 y diciembre 9 de 2015) y 2 en la época seca (febrero 4 y marzo 4 de 2016). Con base en esta información y la carga animal se calculó la producción de peso vivo por hectárea.

Producción de carne. Al final de la ceba, cuando los animales alcanzaron un peso vivo mínimo, promedio en ayuno, de 500 kg y una condición corporal de 8 en una escala 1 a 9, propuesta por Herd y Sprott (1986), fueron transportados a Bogotá para sacrificio en un frigorífico. Una vez sacrificado se determinó el peso de la canal caliente después de la limpieza de esta y se calcularon las pérdidas (‘merma’) por transporte. El rendimiento en canal se determinó en un grupo de 15 toretes (5 por tratamiento) seleccionados al azar.

Cálculo de costos por tratamiento. Para el efecto se consideraron aquellos ocasionados en los tratamientos de fertilización (T2 y T3) y los ingresos obtenidos por la producción de carne, tomando como referencia los costose ingreso en el tratamiento testigo (T1).

Análisis de la información. Los datos fueron organizados en tablas de Excel y el análisis estadístico se realizó con el programa SAS 9.3. La comparación de medias se realizó mediante la prueba de Tukey (P<0.05).

Resultados

Producción de forraje y cobertura del suelo

La producción de forraje durante 21 días de descanso en época lluviosa fue mayor en T3 (P<0.05), resultando 57% más forraje con relación a T 2 y 60% más en comparación con el testigo sin fertilización, T3 (Cuadro 1). Durante la época seca, la producción se redujo entre 60 y 70% en los 3 tratamientos; no obstante continuó siendo mayor en T3 con 940 kg MS/ha. La cobertura del suelo por el pasto fue de 99–100% (Cuadro 1) lo cual sugiere que en ninguno de los tratamientos la carga animal aplicada fue excesiva.

Calidad nutritiva del forraje

Durante la época de lluvias se observó una respuesta significativa (P<0.05) a la aplicación de urea adicional (T3) no solo en términos de producción de forraje sino también concentración de CP en el pasto (Cuadro 2). Las concentraciones de FDN (73%) y FDA (35%) y la degradabilidad in situ de la materia seca (DISMS; 70%) en el forraje fueron similares entre los tratamientos.

Cuadro 1. Producción de forraje y cobertura del suelo por *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia.

Tratamiento (fertilización)[1]	Producción de forraje durante 21 días de descanso (kg MS/ha)[2]		Cobertura (%)
	Época lluviosa	Época seca	
T1- Testigo (sin fertilización)	958b[3]	613b	99.2b
T2- Básica	979b	665b	99.4ab
T3- Básica+urea	1,540a	940a	100.0a
Significancia	0.003	0.002	0.005
C.V. (%)	27.2	8.1	1.3

[1]Las dosis de fertilizantes aparecen en el texto.
[2]Promedios de 2 y 1 fechas en épocas lluviosa y seca, respectivamente.
[3]Promedios con letras diferentes en la misma columna difieren significativamente según la prueba de Tukey (P<0.05).

Cuadro 2. Calidad nutritiva de *Brachiaria humidicola* cv. Llanero en la época lluviosa con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia.

Tratamiento (fertilización)[1]	Proteína cruda (%)	FDN (%)[2]	FDA (%)	DISMS (%)
T1- Testigo (sin fertilización)	8.1b[3]	73.5	35.8	68.9
T2- Básica	8.4b	73.1	35.9	71.3
T3- Básica+urea	9.9a	73.0	35.1	71.1
Significancia	0.02	ns	ns	ns
C.V. (%)	13.4	3.1	7.3	7.1

[1]Las dosis de fertilizantes aparecen en el texto.
[2]FDN = fibra en detergente neutro; FDA = fibra en detergente ácido; DISMS = degradabilidad in situ de la materia seca.
[3]Promedios con letras diferentes en la misma columna difieren significativamente según la prueba de Tukey ($P<0.05$).

Con el uso del programa LNRS y la calidad nutritiva se calcularon los aportes de nutrientes de cada tratamiento de fertilización. Aunque no se observaron diferencias en la concentración de fibra y DISMS entre tratamientos, la predicción permitió explicar parcialmente la mayor ganancia diaria de peso vivo animal en los tratamientos con fertilización (T2 y T3) vs. el testigo (T1) durante el tiempo de evaluación, y, entre octubre a febrero, entre T3 y T2 (véase Cuadro 4). La predicción mostró que el aporte de nutrientes digestibles totales (NDT), la energía metabolizable (EM), la energía neta para mantenimiento (ENm), la energía neta para ganancia de peso (ENg) y la concentración de proteína total de la ración aumentaron con la fertilización (Cuadro 3).

Carga animal

Con base en la cantidad de MS disponible, las cargas animal iniciales fueron de 2.0, 3.0 y 3.8 UA/ha para aumentar a 3.0, 4.2 y 5.3 UA/ha en los tratamientos T1, T2 y T3 al finalizar la época de lluvias, respectivamente. Al comienzo de la época seca el 50% de los toretes alcanzaron un peso promedio de 520 kg y salieron del experimento para sacrificio. De esta forma, y teniendo en cuenta la menor disponibilidad de forraje en la época seca, la carga animal se redujo a 1.6, 2.1 y 3.2 UA/ha en los tratamientos T1, T2 y T3, respectivamente (Figura 2).

Ganancia de peso y producción animal

Las ganancias diarias de peso de los toretes en los tratamientos con fertilización no presentaron diferencias en el primer y segundo pesaje de la época lluviosa ($P>0.05$) con promedios de 837 y 857 g/an/día. No obstante fueron superiores ($P<0.05$) al testigo sin fertilización (Cuadro 4). Durante el último pesaje de la época lluviosa, los animales de T3 presentaron la mayor ganancia de peso (916 g/an/día) ($P<0.05$). Esta ganancia se sostuvo en el período siguiente de diciembre–febrero, correspondiente a la transición de época lluviosa a seca y parte de la época seca. Al finalizar la época seca (febrero–marzo) las ganancias de peso vivo se redujeron en todos los tratamientos, aunque en los tratamientos con fertilización fueron significativamente mayores que el testigo en 333 g/an/día.

En la Figura 3 se resumen las ganancias diarias por animal obtenidas en los tratamientos en las épocas lluviosa y seca y se confirma la superioridad de los tratamientos de fertilización. Las ganancias diarias adicionales en los tratamientos con fertilización fueron de 290 y 190 g/an/día en época lluviosa para T3 y T2, y en la época seca 342 y 263 g/an/día, respectivamente. Es necesario mencionar que durante 15 años anteriores al ensayo, el área experimental recibió cada 2 años una fertilización de mantenimiento. Esto explica las mayores

Cuadro 3. Cálculo de aportes de energía[1] y proteína por LNRS de *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia.

Tratamiento (fertilización)[2]	NDT (% MS)	EM (Mcal/kg)	ENm (Mcal/kg)	ENg (Mcal/kg)	Proteína total (g/día)
T1- Testigo (sin fertilización)	57	2.05	1.20	0.64	713
T2- Básica	58	2.08	1.23	0.66	773
T3- Básica+urea	61	2.21	1.35	0.77	891

[1]NDT = nutrientes digestibles totales; EM = energía metabolizable; ENm = energía neta para mantenimiento; ENg = energía neta para ganancia de peso; Mcal = megacalorías.
[2]Las dosis de fertilizantes aparecen en el texto.

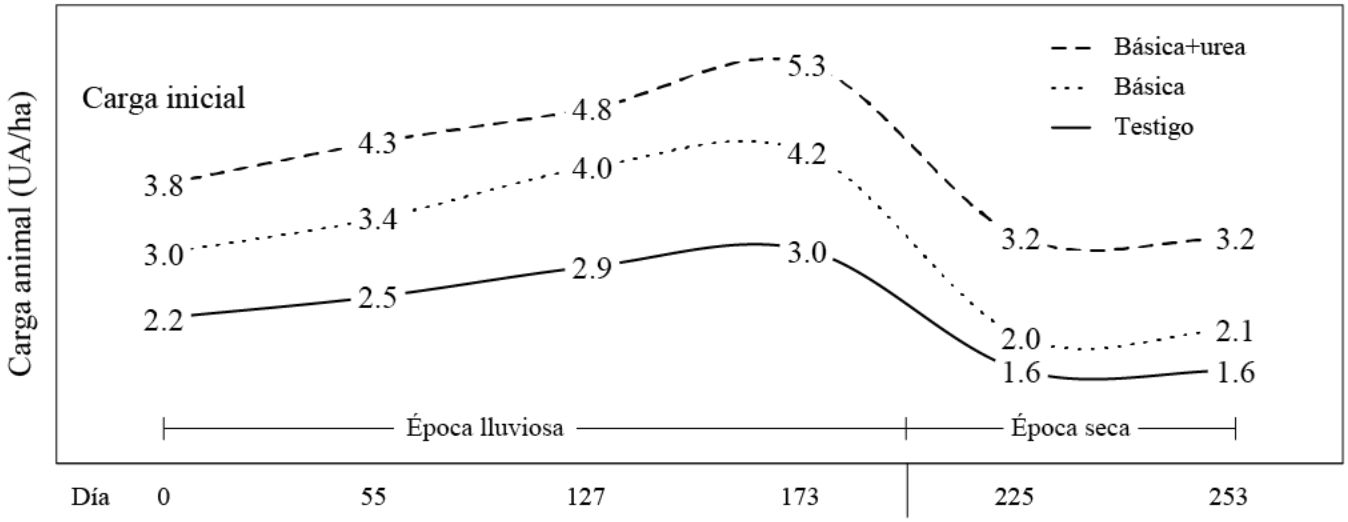

Figura 2. Evolución de la carga animal en *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia. (1 UA = 400 kg de peso vivo.)

Cuadro 4. Ganancia diaria de peso por animal en las épocas lluviosa y seca en *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia.

Tratamiento (fertilización)[1]	Época lluviosa (2015)			Época seca (2016)	
	Pesaje 1 (ago 11)	Pesaje 2 (oct 23)	Pesaje 3 (dic 9)	Pesaje 1 (feb 4)	Pesaje 2 (mar 4)
T1- Testigo (sin fertilización)	0.652b[2]	0.705b	0.445c	0.580c	0.178b
T2- Básica	0.824a	0.842a	0.679b	0.789b	0.495a
T3- Básica+urea	0.850a	0.873a	0.916a	0.913a	0.528a
Significancia	0.002	0.005	0.001	0.01	0.03
C.V. (%)	19.5	14.7	26.4	17.8	24.2

[1]Las dosis de fertilizantes aparecen en el texto.
[2]Promedios con letras diferentes en la misma columna difieren significativamente según la prueba de Tukey (P<0.05).

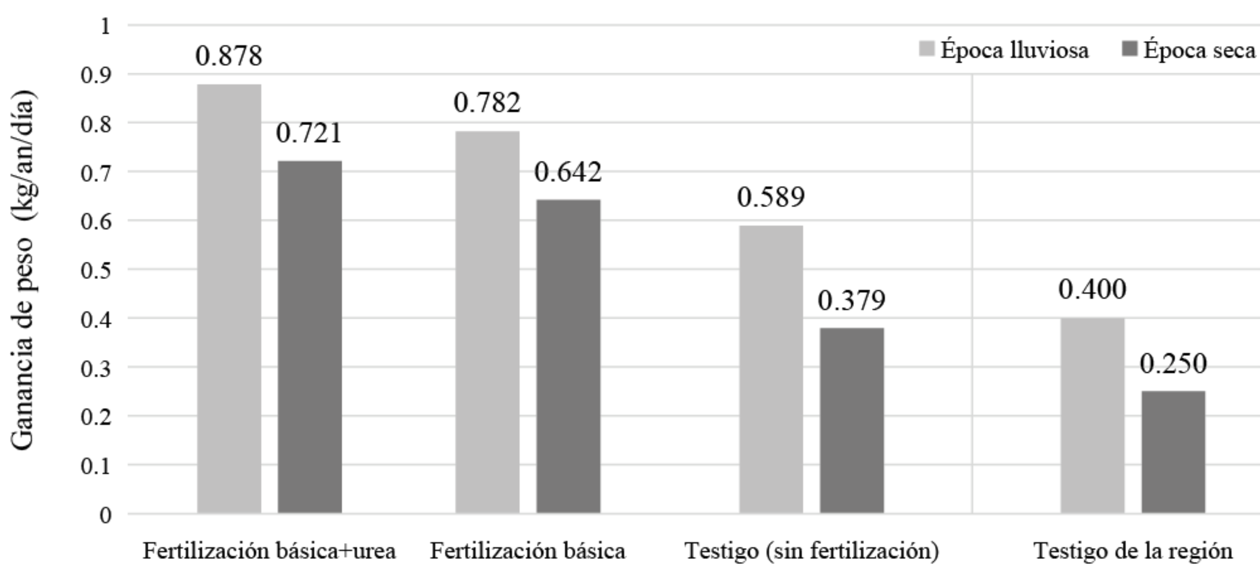

Figura 3. Ganancia diaria de peso/animal en las épocas lluviosa y seca en *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia. (Testigo de la región = ganancia de peso en ganaderías tradicionales en la región, caracterizadas por falta de fertilización.)

ganancias de peso en comparación con el testigo de la región, en pasturas de manejo tradicional (sin fertilización de mantenimiento) y donde las ganancias diarias son en promedio 33% menores, con cargas animal de 2.0 y 1.5 UA/ha durante las épocas lluviosa y seca, respectivamente (Pérez et al. 2000).

Con base en las ganancias diarias de peso y la carga animal durante los 250 días de experimentación (173 días en época lluviosa y 77 días en época seca) se hizo el cálculo de la producción animal por hectárea durante este período. En la época de lluvias, en los tratamientos T2 y T3 se produjeron, respectivamente, 194 y 422 kg/ha de peso vivo más que en el testigo sin fertilización. Durante la época seca, estas diferencias fueron de 77 y 131 kg de peso vivo (Cuadro 5).

Rendimiento en canal y valor comercial

El peso a sacrificio y en canal, los rendimientos y el valor comercial de venta de los animales se presentan en el Cuadro 6. La única diferencia entre los tratamientos es el valor comercial de venta algo más alto para los toretes del tratamiento T3 en comparación con los de T1 (diferencia de US$ 42.5/animal) y T2 (diferencia de US$ 36.8/animal). Esta diferencia es debida al mayor peso de los animales en el tratamiento T3 y a la menor pérdida ('merma') de peso durante el transporte al frigorífico.

Rentabilidad

Para el cálculo de rentabilidad de la fertilización, se utilizaron los costos comerciales de los insumos que aparecen en el Cuadro 7, incluyendo la mano de obra para preparación y aplicación de los fertilizantes.

Con base en los datos presentados en los Cuadros 5, 6 y 7 es evidente la ventaja económica de la fertilización básica+urea. En este tratamiento (T3) se produjeron 870 kg de peso vivo/ha durante los 250 días de pastoreo, que generaron un ingreso bruto de US$ 1,414 tomando como base un precio de venta de US$ 1.63 por kilo de carne en pie y un ingreso neto de US$ 1,173, mientras que en el tratamiento con fertilización básica (T2) se produjeron 599 kg de peso vivo/ha con un ingreso de US$ 973 por venta de ganado en pie y de US$ 823 como ingreso neto (Cuadro 8). Cuando estos resultados se comparan con los obtenidos en el tratamiento testigo (T1, sin fertilización)

Cuadro 5. Producción de peso vivo animal en pasturas de *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia.

Tratamiento (fertilización)[1]	Época lluviosa (kg/ha - 173 días)	Época seca (kg/ha - 77 días)	Total (kg/ha - 250 días)
T1- Testigo (sin fertilización)	270	47	317
T2- Básica	498	101	599
T3- Básica+urea	692	178	870

[1]Las dosis de fertilizantes aparecen en el texto.

Cuadro 6. Peso al sacrificio, merma, rendimiento en canal y valor comercial de venta (en US dólares) de toretes Cebú Brahman en pasturas de *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia. (1 US$ = Col.$ 2,800.)

Variable	Fertilización[1]			Significancia	C.V. (%)
	T1	T2	T3		
Peso salida a frigorífico (kg/an)	546	545	566	ns	2.8
Peso en frigorífico (kg/an)	508	511	534	ns	2.9
Merma por transporte (% peso)	7.04	6.24	5.76	ns	16.0
Merma por transporte (valor US$/kg)	0.114	0.101	0.094	ns	16.1
Peso canal caliente (kg/an)	307	310	319	ns	2.0
Rendimiento en canal (%)	60.5	60.4	59.7	ns	1.2
Total descuentos[2] (US$/kg)	0.17	0.16	0.15	ns	11.8
Valor kilo con descuentos[3] (US$)	1.46	1.47	1.48	ns	1.3
Valor comercial de venta por animal (US$)	795	801	838	0.05	3.1

[1]Las dosis de fertilizantes aparecen en el texto.
[2]Incluye pago por transporte, pesaje e impuestos por animal.
[3]Valor kilo de venta sin descuento: US$ 1.63.

Cuadro 7. Costos de la fertilización para los tratamientos de fertilización en *Brachiaria humidicola* cv. Llanero. C.I. La Libertad, Villavicencio, Colombia. (1 US$ = Col.$ 2,800.)

Detalle	T2 -Fertilización básica		T3 -Fertilización básica+urea	
	Cantidad (kg/ha)	Valor (US$/ha)	Cantidad (kg/ha)	Valor (US$/ha)
Urea	0	0	200	86
Fosfato diamónico (DAP)	100	54	100	54
Sulpomag	100	50	100	50
Sulcamag	100	36	100	36
Mano de obra (jornales)	1	11	1.5	16
Valor total		150		241

Cuadro 8. Ingresos netos obtenidos por la producción de carne bovina en *Brachiaria humidicola* cv. Llanero con 3 tratamientos de fertilización. C.I. La Libertad, Villavicencio, Colombia. (1 US$ = Col.$ 2,800.)

Fertilización[1]	Precio de venta peso vivo animal (US$/ha)	Costo de fertilización (US$/ha)	Ingreso neto (US$/ha)	Ingreso adicional con respecto al testigo (US$/ha)
T1-Testigo (sin fertilización)	515	0	515	
T2- Básica	973	150	823	308
T3- Básica+urea	1,414	241	1,173	658

[1]Las dosis de fertilizantes aparecen en el texto.

se observa un mayor ingreso/ha de US$ 658 en el tratamiento T3 y de US$ 308 en el tratamiento T2. Lo anterior significa que con una inversión por hectárea de US$ 91 en la fertilización nitrogenada se obtiene un ingreso adicional de US$ 350, en comparación con el tratamiento de fertilización básica, equivalente a US$ 3.80 por cada dólar invertido en urea como fertilizante.

Discusión

Los resultados obtenidos en este estudio muestran las ventajas de una adecuada fertilización del pasto *B. humidicola* cv. Llanero en el Piedemonte de los Llanos Orientales de Colombia, especialmente con la aplicación de N, y el potencial de este pasto para mejorar la capacidad de carga animal y las ganancias de peso vivo de bovinos en ceba. El incremento del 45% en la producción de peso vivo que se obtiene con la adición de 92 kg N/ha justifica la inversión y demuestra la importancia de este nutriente para la producción y calidad del forraje.

Es ampliamente reconocido que la aplicación de N mejora tanto la producción de un pasto como la concentración de PC en el forraje (García et al. 2002; Rincón y Ligarreto 2011; Pérez 2014; Crespo et al. 2015; Dupas et al. 2016; Valbuena et al. 2016). El efecto positivo de la fertilización nitrogenada sobre la digestibilidad, el valor energético y la proteína metabolizable del forraje también fue demostrado por Peyraud y Astigarraga (1998) y Johnson et al. (2001). Esto es de mayor importancia en suelos con bajo contenido de materia orgánica como los de la Orinoquia colombiana, donde no es común la mezcla de pasturas gramíneas-leguminosas ni la fertilización. Aunado a esto, el alto costo de las fuentes nitrogenadas como la urea ha limitado su uso por parte de los productores en la región, lo que se refleja en los bajos índices de producción de carne o leche bovina, como consecuencia tanto de la baja producción como bajo valor nutritivo, especialmente concentración de PC (5–8%), de los forrajes comúnmente usados en la región. No obstante que en este trabajo no se estudiaron los efectos de otros nutrientes incluidos en la fertilización básica, es necesario destacar su potencial aporte al sistema productivo, especialmente en el tipo de suelos donde se desarrolló el experimento, caracterizados por la deficiencia de la mayoría de nutrientes esenciales para el crecimiento y la producción de las plantas (Ayarza 1991).

La producción de peso vivo animal (870 kg/ha) obtenida en 250 días de ceba en pastoreo, confirma la respuesta positiva de los animales cuando tienen acceso a un pasto de buena calidad y en cantidad suficiente, que permite aumentar tanto la capacidad de carga animal por hectárea como la producción por animal. Este resultado es de impacto potencial para la ganadería en la región, si se compara con la producción de peso vivo animal por hectárea de, en promedio, 180 kg/ha/año en pasturas manejadas en forma tradicional y por tanto en proceso de degradación (Rincón 2006). Un resultado similar fue reportado por Rincón (2004) para la Altillanura bien drenada de los Llanos Orientales de Colombia donde con una fertilización básica (kg/ha: P 24, Ca 90, Mg 30, S 20 y N 50) de una pastura de *B. decumbens* se obtuvo una producción de peso vivo de 397 kg/ha/año en comparación con 193 kg sin fertilización.

En vista de la evidente importancia de la fertilización nitrogenada de pastos en la región es indicado estudiar la optimización de su aplicación. Se requieren de estudios sobre la eficiencia de la utilización y de la recuperación de N fertilizado no solo con miras a la rentabilidad de la producción sino también por el alto potencial que el N tiene para contaminar el medio ambiente (lixiviación de nitratos, emisión del potente gas de efecto invernadero, N_2O) (Byrnes 1990; Orozco 1999).

Conclusiones

Por el valor nutritivo, la aceptable producción de MS y la rentabilidad que presenta para el productor ganadero en el Piedemonte de la Orinoquia colombiana, *B. humidicola* cv. Llanero adecuadamente fertilizado es una alternativa rentable de producción. Se considera que también es una opción para el pequeño productor en la región ya que con 10 hectáreas de cv. Llanero fertilizadas puede obtener un ingreso de casi US$ 15,000/año.

Los resultados confirman el potencial que pastos introducidos o mejorados tienen para contribuir a una mayor producción ganadera. Se espera que este estudio aporte a la implementación de la Estrategia Colombiana de Desarrollo Bajo en Carbono mediante, entre otras, la Acción de Mitigación Nacionalmente Apropiada (*NAMA*, su sigla en inglés) denominada '*Ganadería Bovina Sostenible*' que busca reducir el área actualmente utilizada para la producción ganadera mediante intensificación sostenible (Gobierno de Colombia 2015).

Referencias

(Nota de los editores: Todos los enlaces fueron verificados el 9 de septiembre de 2018.)

Amézquita MC. 1986. Consideraciones sobre planeación, diseño y análisis de experimentos de pastoreo. En: Lascano C; Pizarro E, eds. Evaluación de pasturas con animales: Alternativas metodológicas. Memorias de una reunión de trabajo celebrada en Perú, 1–5 de octubre, 1984, Red Internacional de Evaluación de Pastos Tropicales (RIEPT). Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p. 13–43. hdl.handle.net/10568/56361

AOAC (Association of Official Agricultural Chemists). 1995. Official methods of analysis. 16th Edn. AOAC Inc., Arlington, VA, USA.

Ayarza MA. 1991. Efecto de las propiedades químicas de los suelos ácidos en el establecimiento de las especies forrajeras. En: Lascano CE; Spain JM, eds. Establecimiento y renovación de pasturas: Conceptos, experiencias y enfoque de la investigacion. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p. 161–185. hdl.handle.net/10568/56475

Byrnes BH. 1990. Environmental effects of N fertilizer use – An overview. Fertilizer Research 26:209–215. DOI: 10.1007/BF01048758

Crespo G; Rodríguez I; Lok S. 2015. Contribución al estudio de la fertilidad del suelo y su relación con la producción de pastos y forrajes. Revista Cubana de Ciencia Agrícola 41:211–219. goo.gl/dSogXf

CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2007. Nutrient requirements of domesticated ruminants. CSIRO Publishing, Collingwood, VIC, Australia. goo.gl/nrb5yt

Dupas E; Buzetti S; Rabêlo FHS; Sarto AL; Cheng NC; Teixeira Filho MCM; Galindo FS; Dinalli RP; Gazola RN. 2016. Nitrogen recovery, use efficiency, dry matter yield, and chemical composition of palisade grass fertilized with nitrogen sources in the Cerrado biome. Australian Journal of Crop Science 10:1330–1338. DOI: 10.21475/ajcs.2016.10.09.p7854

Fox DG; Tedeschi LO; Tylutki TP; Russell JB; van Amburgh ME; Chase LE; Pell AN; Overton TR. 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Animal Feed Science and Technology 112:29–78. DOI: 10.1016/j.anifeedsci.2003.10.006

García F; Micucci F; Rubio G; Ruffo M; Daverede I. 2002. Fertilización de forrajes en la región pampeana: Una revisión de los avances en el manejo de la fertilización de pasturas, pastizales y verdeos. Instituto de la Potasa y el Fósforo (INPOFOS) Cono Sur, Acassuso, Argentina. goo.gl/7CDDEy

Gobierno de Colombia. 2015. Nota de información de la NAMA Ganaderia Bovina Sostenible: Densificación productiva, reconversión de pasturas y devolución a la naturaleza. Estrategia Colombiana de Desarrollo Bajo en Carbono (ECDBC), Bogotá, Colombia. goo.gl/JRpw5A

Herd DB; Sprott LR. 1986. Body condition, nutrition and reproduction of beef cows. Texas Agricultural Extension Service. The Texas A&M University System, College Station, TX, USA. goo.gl/6Uir1F

ICA (Instituto Colombiano Agropecuario). 1987. Pasto Llanero *Brachiaria dictyoneura* (Fig. & De Not.) Stapf. Boletín técnico No. 151. ICA, Villavicencio, Colombia. goo.gl/XRi9KZ

Johnson CR; Reiling BA; Mislevy P; Hall MB. 2001. Effects of nitrogen fertilization and harvest date on yield, digestibility, fiber, and protein fractions of tropical grasses. Journal of Animal Science 79:2439–2448. DOI: 10.2527/2001.7992439x

Martha Júnior GB; Vilela L; Barioni LG; Sousa DMG; Barcellos AO. 2004. Manejo da adubação nitrogenada em pastagem. En: Pedreira CGS; Moura JC de; Faria VP de, eds. Fertilidade do solo para pastagens produtivas. Anais do 21° Simpósio sobre manejo da pastagem: Fundação de Estudos Agrários Luiz de Queiroz (FEALQ), Piracicaba, SP, Brasil. p. 155–215.

Minson DJ. 1973. Effect of fertilizer nitrogen on digestibility and voluntary intake of *Chloris gayana, Digitaria decumbens* and *Pennisetum clandestinum.* Australian Journal of Experimental Agriculture and Animal Husbandry 13:153–157. DOI: 10.1071/ea9730153

MLA (Meat and Livestock Australia). 2006. Beef cattle nutrition: An introduction to the essentials. MLA, North Sydney, NSW, Australia. goo.gl/M5Z4V3

Nocek JE; English JE. 1986. In situ degradation kinetics: Evaluation of rate determination procedure. Journal of Dairy Science 69:77–87. DOI: 10.3168/jds.s0022-0302(86)80372-1

Orozco FH. 1999. La biología del nitrógeno: Conceptos básicos sobre sus transformaciones biológicas. Universidad Nacional de Colombia, Medellín, Colombia. goo.gl/N3W9Z1

Parsons D; Nicholson CF; Blake RW; Ketterings QM; Ramírez-Avilés L; Fox DG; Tedeschi LO; Cherney JH. 2011. Development and evaluation of an integrated simulation model for assessing smallholder crop-livestock production in Yucatán, Mexico. Agricultural Systems 104:1–12. DOI: 10.1016/j.agsy.2010.07.006

Pérez O. 2014. Eficiencia del uso del nitrógeno en pasturas de *Panicum maximum* y *Brachiaria* sp. solas y asociadas con *Pueraria phaseoloides* en la altillanura colombiana. Tesis de maestría. Universidad Nacional de Colombia, Bogotá, Colombia. bdigital.unal.edu.co/46432

Pérez RA; Rincón A; Bueno G; Vargas O; Cuesta P. 2000. Alternativas de establecimiento de praderas. Innovación y Cambio Tecnológico 1(2):56–61.

Peyraud JL; Astigarraga L. 1998. Review of the effect of nitrogen fertilization on the chemical composition, intake, digestion and nutritive value of fresh herbage: Consequences on animal nutrition and N balance. Animal Feed Science and Technology 72:235–259. DOI: 10.1016/s0377-8401(97)00191-0

Rincón A. 2004. Rehabilitación de pasturas y producción animal en *Brachiaria decumbens* en la altillanura plana de los Llanos Orientales de Colombia. Pasturas Tropicales 26(3):2–12. goo.gl/3Ts78i

Rincón A. 2006. Factores de degradación y tecnología de recuperación de praderas en los llanos orientales de Colombia. Boletín técnico No. 49. Corpoica, Villavicencio, Colombia. hdl.handle.net/11348/3791

Rincón A. 2011. Efecto de alturas de corte sobre la producción de forraje de *Brachiaria* sp. en el piedemonte llanero de Colombia. Revista Corpoica - Ciencia y Tecnología Agropecuaria 12:107–112. 10.21930/rcta.vol12_num2_art:219

Rincón A. 2012. Concentración de minerales en suelos y fertilización de pastos en los Llanos Orientales de Colombia. En: Rincón A; Baquero JE; Flórez H; Jaramillo CA, eds. Manejo de la nutrición mineral en sistemas ganaderos de los Llanos Orientales de Colombia. Corpoica, Villavicencio, Colombia. p. 113–164. goo.gl/DawbXw

Rincón A; Ligarreto GA. 2011. Effect of nitrogen over corn-grass association in renovation of pastures at piedemont of the Llanos Orientales of Colombia. Agronomía Colombiana 29:91–98. goo.gl/HkD91T

Salinas JG; García R. 1985. Métodos químicos para el análisis de suelos ácidos y plantas forrajeras. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. hdl.handle.net/10568/54174

Salisbury FB; Ross CW. 1992. Fisiología vegetal. 4ª Edn. Grupo Editorial Iberoamericana, México, DF. p. 319–338.

Valbuena N; Tejos R; Terán Y. 2016. Efecto de la fertilización nitrogenada e intervalo entre cortes sobre contenido de proteína y fibra en *Brachiaria brizantha* cv. Toledo en Portuguesa. Revista Unellez de Ciencia y Tecnología 34:25–32. goo.gl/61vmNQ

Van Soest PJ. 1963. Use of detergent in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. Journal of the Association of Official Analytical Chemists 46:829–835. goo.gl/tAmbLm

Van Soest PJ; Wine RH. 1967. Use of detergent in the analysis of fibrous feeds. IV. Determination of plant cell/wall constituents. Journal of the Association of Official Analytical Chemists 50:50–55. goo.gl/HhyMLS

(Received for publication 27 February 2018; accepted 1 September 2018; published 30 September 2018)

DOI: 10.17138/TGFT(6)169-176

Research Paper

Ecological implications of bush encroachment on foraging behavior of dairy cows and goats at SUA farm, Morogoro, Tanzania

Implicaciones ecológicas de la colonización de especies leñosas en el comportamiento del pastoreo de vacas y cabras lecheras en SUA Farm, Morogoro, Tanzania

ISMAIL S. SELEMANI

Department of Animal, Aquaculture and Range Sciences, Sokoine University of Agriculture (SUA), Morogoro, Tanzania. www.coa.sua.ac.tz/aanimal

Abstract

The study was carried out at SUA Magadu Farm to investigate the influence of bush encroachment in a native rangeland on foraging behavior and grazing distribution of dairy cows and goats. Characterization of bush in terms of woody density was done using the PCQ method. A mixture of animals (150 cows and 60 goats) were rotationally grazed on areas with 3 different levels of bush encroachment (dense - 60%; moderate - 35%; and open grassland - ≤5%) and grazing behavior of 3 cows and 3 goats was monitored. Six trained observers recorded behavior of these animals for 2 hours in the morning and 2 hours in the afternoon for 9 days on a rotational basis. There were significant interactions between animal species in terms of grazing behavior and level of bush encroachment. Both species spent similar amounts of time grazing on open grassland (>75% of total feeding time) but on treatments with moderate and dense bush encroachment levels goats spent at least 70% of their time browsing, while grazing time of cows did not change. Goats took many more bites than cows on all treatments and as a result spent more time walking than cows. The implications of these findings for management of bush encroachment are discussed. Further studies on nutritive values and chemical composition of key forage species in the study area are recommended as well as the changes in behavior with different seasons and the impacts on animal production.

Keywords: *Acacia* spp., bite rate, feeding, focal observation, spatial distribution.

Resumen

En el SUA Magadu Farm, Morogoro (37°39' E, 06°05' S; 500–600 msnm), Tanzania, se evaluó el efecto de la colonización de especies leñosas (sobre todo *Acacia* spp.) en el comportamiento del pastoreo de vacas y cabras lecheras en un pastizal nativo compuesto por una diversidad de gramíneas de variable utilidad forrajera. Las lecturas de la densidad de especies leñosas (matorrales) se hizo utilizando el método PCQ. Para el efecto, se empleó un grupo de animales compuesto por una mezcla de 150 vacas y 60 cabras que pastaron en forma rotacional en áreas con 3 niveles diferentes de densidad de vegetación leñosa (denso - 60%, moderado - 35% y campo abierto - ≤5%). Se escogieron al azar 3 vacas y 3 cabras para la toma de datos por 6 observadores entrenados, quienes registraron el comportamiento de estos animales durante 2 horas en la mañana y 2 horas en la tarde por un período de 9 días en forma rotatoria. Los resultados mostraron interacciones ($P<0.05$) entre las especies animal en términos de comportamiento del pastoreo, y la densidad de las especies leñosas. En campo abierto tanto las vacas como las cabras permanecieron períodos similares de tiempo pastando (>75% del total de tiempo usado para pastoreo más ramoneo); por otra parte, en los niveles moderados y densos de vegetación leñosa las cabras permanecieron al menos 70% de su tiempo ramoneando, mientras que el tiempo

Correspondence: I.S. Selemani, Department of Animal, Aquaculture and Range Sciences, Sokoine University of Agriculture (SUA), P.O. Box 3004, Morogoro, Tanzania.
Email: suma02seleman@yahoo.co.uk

de pastoreo de las vacas no cambió. Las cabras tomaron un número muy mayor de bocados que las vacas en todos los tratamientos y consecuentemente pasaron más tiempo caminando que las vacas. Se discuten las implicaciones de estos resultados para el manejo de las especies leñosas en pastizales. Se recomiendan estudios sobre el valor nutritivo y la composición química de las especies forrajeras más importantes en el área de estudio, así como sobre los cambios en el comportamiento de pastoreo en función de la época de año y su impacto en la producción animal.

Palabras clave: *Acacia* spp., distribución espacial, observación focal, pastoreo, tasa de bocado, vegetación leñosa.

Introduction

Over the past 50 years the semi-arid savanna ecosystems throughout the world have suffered severe bush encroachment (Britz and Ward 2007; Kambatuku et al. 2011), which is associated with the reciprocal competitive interaction between trees and grasses (Kambatuku et al. 2011). Although bush encroachment is associated with heavy grazing pressure by livestock (Tefera et al. 2007), wildfire and effects of climate change (O'Connor and Chamane 2012), the ecological implications are poorly understood. Many studies, e.g. Ward (2005) and Tefera et al. (2007), suggested that bush encroachment reduces grazing capacity through suppression and replacement of palatable grasses and herbs by encroaching woody species, which often are unpalatable to domestic livestock, resulting in reduced carrying capacity. The decrease in grazing capacity has significant ecological and sociological implications because semi-arid savanna ecosystems in Africa are home to a large proportion of the world's human population, including many pastoralists, whose livelihoods are threatened by this process (Gowing and Palmer 2008).

Interestingly, woody plants are normally not considered when estimating carrying capacity of grazing land, despite their importance as a cheap source of fodder for ruminants (Moleele 1998). Knowledge of the ruminant-woody plant interaction is most important for appropriate management of livestock and vegetation, particularly in semi-arid savanna ecosystems (Thomas and Twyman 2004). Moleele (1998) hypothesized that animals normally respond to harsh conditions by modifying their grazing behavior to meet their nutritional requirements. Therefore, understanding the consequences of increasing bush encroachment on foraging behavior of dairy cows and goats is imperative for determining effective management strategies. To understand the ecological implications of woody encroachment on livestock performance and carrying capacity of rangeland, quantitative data on woody plant density and distribution in relation to how grazing animals respond to bush encroachment are required. Currently, there is limited information on foraging behavior of both dairy cows and goats in these situations, particularly how they respond to spatial heterogeneity following bush encroachment.

Animal distribution on rangeland has ecological implications in terms of nutrient extraction and ecosystem impact. For example, uneven distribution of grazing animals can threaten ecosystem health by exacerbating processes of deterioration such as soil erosion (Bailey et al. 1996). Most rangeland resources are heterogeneous due to a combination of biotic and abiotic factors and therefore rangeland utilization is rarely uniform (Vermeire et al. 2004). Encroachment of bush or weeds, poor distribution of water resources and frequency of burning normally result in a patchy distribution of forage resources, which strongly influences animal grazing behavior.

Increases in livestock populations in Tanzania have been associated with changes in composition of vegetation from grassland to woodland (Wiskerke et al. 2010). Currently, Tanzania is ranked second in terms of livestock population in Africa with 25 M cattle, 16.7 M goats and 8 M sheep (MLFD 2015). Over-utilization of rangeland resources in parts of the country has resulted in transformation of previous grassland ecosystems to dense woodland, accompanied by poor production of the herbaceous layer (Selemani et al. 2013a). The predominant woody plants in most rangelands in Tanzania are *Acacia* spp., which may reflect overgrazed land, as *Acacia* trees have the ability to tolerate heavy grazing pressure and thrive well in degraded rangelands (Tefera et al. 2007). The shift from grassland to woodland ecosystems should have ecological implications, particularly for grazing animals, in terms of behavioral responses, grazing distribution and utilization of available resources. Information regarding the impacts of vegetation change on behavioral responses of different classes of livestock is crucial for sustainable livestock production and rangeland management.

The current study was undertaken to: 1) assess the influence of different levels of bush cover on foraging behavior of dairy cows and goats; and 2) determine the effects of bush encroachment on grazing distribution of dairy cows and goats. The study hypothesized that accessibility of fodder on areas with heavy bush encroachment is restricted for foraging animals and thus affects stock distribution, method of foraging and choice of type of forage.

Methodology

Description of study area

The study was conducted at SUA Magadu Dairy Farm about 5 km from Morogoro Municipal (37°39' E, 06°05' S; 500–600 masl). Average annual temperature in the region is 18 °C but sometimes reaches 30 °C in the lowland river valleys. Rainfall is bi-modal, averaging 600–900 mm per annum (Paavola 2004). Short rains often occur in November–December, followed by a short dry period in January–February, with heavy rain normally falling in March–May and a long dry season in June–November. The agro-ecological zone of Magadu Farm is low mountainous country below the slopes of Uluguru Mountain and the common vegetation is a mixture of grassland and woodland. The study area has increasingly become populated by woody plants, largely dominated by *Acacia nilotica*, *A. seyal* and *A. tortilis*. The dominant desirable native grass species are *Urochloa mosambicensis, Bothriochloa pertusa*, *Cynodon nlemfuensis, C. dactylon* and *Hyparrhenia* spp., while the common undesirable grasses are *Sporobolus* spp. However, useful originally planted grass species such as Napier grass (*Pennisetum purpureum*), Rhodes grass (*Chloris gayana)* and buffel grass (*Cenchrus ciliaris)* are also present. The farm is heavily infested with notorious invasive species, noted species being *Lantana camara* and *Solanum incanum,* which are quite prevalent in bushland. Soils of the study area are primarily sandy (12% clay, 4% silt and 84% sand) with pH of 6.6, 0.12% total N, 46.2 mg available P/kg and 0.61 mg K/g (Kizima et al. 2014). The common livestock on the farm are cattle, goats, sheep and horses.

Research design and sampling procedures

Prior to behavioral observations, a vegetation survey was conducted to characterize the status of woody en-+croachment in SUA Magadu Farm. The Point Centered Quarter (PCQ) method of Cottam and Curtis (1956) was used to estimate woody density and percentage crown cover. The farm was stratified into 3 subplots (approx.-imately 40 ha dense bush, 45 ha moderate bush and 50 ha open grassland) based on the extent of woody encroachment from visual observation. In each subplot 2 diagonal transect lines were established. Along transect lines, the cross-points (with 4 quarters) were marked at 50 m intervals, the nearest woody species were identified from each quarter and their distances from the center were measured. In addition, crown diameter of each identified woody species was recorded. Finally, absolute woody density and percentage crown cover of each subplot were estimated. Absolute density (λ) is defined as the number of trees per unit area and is calculated as: $\lambda = 1/r^2$, where r = mean quarter distance obtained by dividing sums of all quarter distances by number of trees sampled. The λ is easily estimated per square meter so λ is multiplied by 10,000 to express as number of trees per ha (Mitchell 2007; Volpato et al. 2010). Areas of individual trees were calculated and percentage cover was computed by comparing total areas of subplots and total areas covered by trees as described by Mitchell (2007).

The behavioral observation study was carried out between the end of the short dry season and the onset of the heavy rainy season in March 2017. Despite spatial variation in production of the herbaceous layer following bush encroachment, growth rates of grasses and herbs during the rainy season are generally superior to those in the dry season (Kizima et al. 2014). For the behavioral study we used focal observation procedures as described by Martin and Bateson (2007). Six focal animals, 3 Friesian dairy cows and 3 Toggenburg dairy goats, were randomly selected from the groups of 150 cows and 60 goats for behavioral observation. Friesian dairy cows and Toggenburg goats were studied because of their significant economic contribution to Tanzania's dairy industry (Njombe et al. 2011). All selected focal animals were ear-tagged for ease of identification in the field during observations. All animals (150 cows and 60 goats) were rotationally grazed as a group (dense bush, moderate bush and open grassland) with a full grazing cycle occupying 9 days (3 days per subplot). All animals were housed at night and in the middle of the day and allowed to graze only during 08:00–12:00 h and 14:00–17:00 h. Six trained observers were responsible for recording the behavioral activities exhibited by the focal animals. Observations were continued for 2 hours in the morning and 2 hours in the afternoon each day for 3 days consecutively for each subplot. To reduce the influence of bias by individual observers, observers were allocated a different focal animal each day. The parameters recorded included time spent (in seconds) in different behavioral activities, e.g. grazing, browsing, walking, ruminating, idling and other. Observations were carried out for 5 minutes followed by a 5 minute break, giving 50% of actual observation and another 50% for recording parameters. An animal was considered to be idling when standing or lying without feeding or ruminating. Other parameters recorded were: number of bites, number of patches visited and number of feeding stations. A patch was defined by aggregation of forage species, where an animal initiates grazing before reorienting (moving) to another location, and a feeding station was distinguished by a given head position without moving the feet (Adler et al. 2001).

Statistical analysis of data

The Proc Mixed Model of SAS (2004) was used to analyze the fixed main effects of bush cover (thick bush, moderate bush and open grassland), livestock species (cows and goats) and the two-way interaction effect of bush cover x animal species. Observers, days and residual were treated as random effects in this model while individual animal's measurements (ID) were tested as repeated measures within different bush levels. Treatment differences were separated using the Least Squares Difference (LSD) as described by Montgomery (2001). For spatial distribution of animals the General Linear Model of SAS (2004) was used to analyze the main effects of bush cover and animal species and interaction effects of bush cover x animal species. The contrasts of the least square means (lsmeans) of the interactions were calculated and tested with the F test at 5% probability. Prior to statistical analysis, the distribution of data for dependent variables was checked using the Anderson-Darling test under proc in SAS (2004) and data were normally distributed.

Results

Range inventory using the PCQ method established that the absolute densities of woody plants (trees/ha) in thick bush, moderate bush and open grassland were: 608 ± 60.4; 355 ± 60.4; and 50.6 ± 60.4 trees/ha, respectively. The corresponding values for percentage crown cover for thick bush, moderate bush and open grassland were: 60; 35; and 5%, respectively. More than 70% of woody species in the study area were *Acacia* spp. dominated by, in descending order, *Acacia nilotica, Acacia tortilis* and *Acacia seyal*. Other woody species were: *Harrisonia abyssinica, Kigelia africana, Dichrostachys cinerea, Senna siamea, Leucaena leucocephala* and *Combretum* spp.

There were significant interactions between bush level and livestock species in terms of foraging behavior as shown in Table 1, although there was obviously some degree of dietary overlap between grazers (cows) and browsers (goats). Grazing was the major activity for cows in all situations and for goats in open grassland, while browsing was the main activity for goats in moderate bush and less so in thick bush. While goats spent the same amount of time grazing as cows in open grassland, they spent much less time grazing than cows in moderate bush with thick bush intermediate, spending significantly more time browsing in areas with significant bush encroachment than dairy cows. In contrast, cows spent slightly more time browsing in open grassland than in bush treatments. Total time devoted to grazing plus browsing by dairy cows was 15% longer on open grassland than on bush treatments, while goats spent 18% more time in these activities when on the bush treatments.

The study recorded a significantly higher number of patches and feeding stations in thick bush and open grassland than in moderate bush, while the number of bites was inversely proportional to bush density (Table 2). Goats visited more patches, had more feeding stations and took twice as many bites as cows (Table 3).

Goats spent little time browsing within a single patch, tending to move quickly to the next patch, especially in open grassland and thick bush (Figure 1A), and maximized bite rate in moderate bush (Figure 1B).

Table 1. The interaction between bush level and livestock species for foraging behavior.

Bush-Livestock		Mean time (seconds) spent per activity for each 5 minute observation period					
		Grazing	Browsing	Walking	Ruminating	Idling	Other
Open grassland	Cows	179.1a[1]	59.7c	18.0d	26.5a	10.9b	6.16b
	Goats	176.4a	38.8e	79.3a	2.23d	0.56c	2.27c
Moderate bush	Cows	157.9b	52.6d	28.9c	20.9b	21.1a	19.8a
	Goats	81.2d	182.5a	32.9c	0.26d	0.00c	1.23c
Thick bush	Cows	154.0b	51.3d	58.2b	15.2c	12.5	8.16b
	Goats	119.2c	146.2b	33.2c	0.00d	0.00c	1.36c
s.e.		2.98	1.88	2.11	1.74	1.46	1.08

[1]Values followed by different letters within columns are significantly different at $P<0.05$.

Table 2. The effect of bush cover on numbers of patches, feeding stations and bites per 5-minutes interval.

Treatment	No. of patches	No. of feeding stations	No. of bites
Open grassland	13.7a[1]	31.6a	98.2a
Moderate bush	11.3b	27.8b	94.4b
Thick bush	13.6a	30.9a	87.5c
s.e.	0.26	0.72	0.91
P value	0.001	0.004	0.001

[1]Values followed by different letters within columns are significantly different at P<0.05.

Table 3. Number of patches, feeding stations and bites for cows and goats per 5-minutes interval.

Animal species	Number of patches	Number of feeding stations	Number of bites
Cows	6.0	18.6	63.8
Goats	19.8	41.6	122.9
s.e.	0.21	0.59	0.74
P value	0.001	0.001	0.001

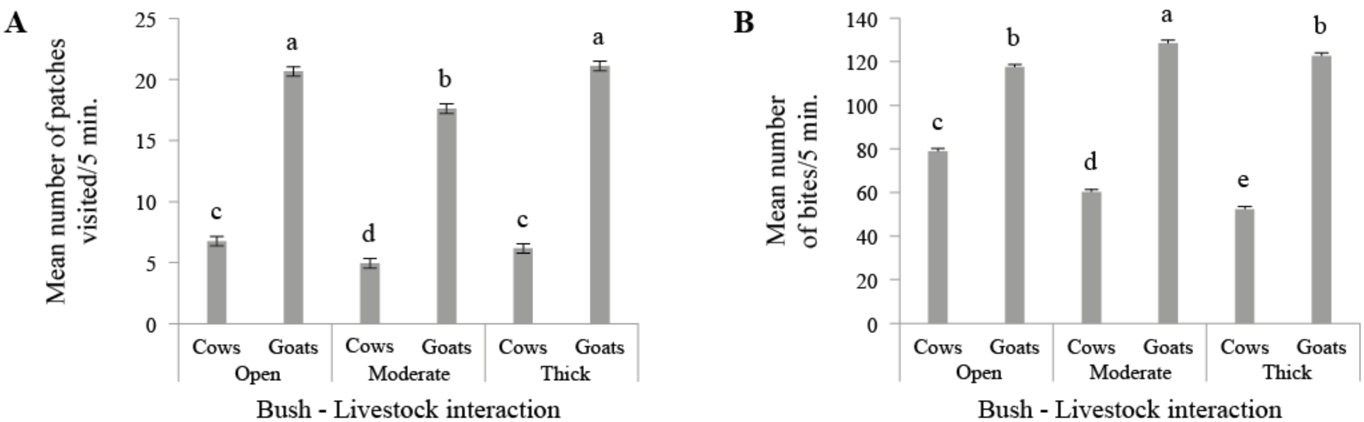

Figure 1. Effect of bush-livestock interaction on: **A)** number of patches; **B)** number of bites.

Discussion

The pattern of declining grazing time as bush density increased is probably associated with changes in herbaceous vegetation because woody encroachment is normally accompanied by decrease in herbaceous production and undesirable shifts in vegetation composition (Tefera et al. 2007). Transformation of grassland to woodland creates sub-habitats which differ from open grassland and hence exert different influences on grazing behavior. Cattle normally prefer grazing on open grassland because of their inherited grazing abilities, morphological and physiological adaptation and security against predation (Coughenour 1991; Bailey et al. 1996; Selemani et al. 2013b). It was interesting that, on open grassland with minimal browse available, time spent grazing by cows and goats was similar, but where there was adequate browse available, goats displayed their preferred habit of spending much more time browsing and actually spent as much time browsing on the moderate bush treatment as they did grazing on open grassland. While cows compensated for the reduced herbage available in bush treatments by limited browsing, their overall feeding time (grazing plus browsing) was reduced, while goats actually increased their overall feeding time where there was adequate browse available.

It was of interest that the highest browsing time by goats was in moderate bush cover. The significant differences in browsing time between moderate and thick bush could be due to differences in growth stage and maturity of woody plants as well as accessibility of browsable materials in these treatments. Thick bush consisted of largely mature, taller trees such as *Acacia nilotica*, and goats had difficulty accessing the foliage as it was often beyond their reach, while moderate bush contained accessible young sprouting leaves following recent bush clearance. According to Illius et al. (1999), selection of plant species and plant parts normally relates to nutritional value and digestibility of the material, taking into account the growth and maturity stage of particular plants. Cows and goats are highly adapted to grazing and browsing, respectively, due to their body morphological structure and digestive ability. However, the notable dietary overlap between goats (browsers) and cows (grazers) in the open grassland was associated with an acute shortage of browsing materials with both species spending more than 75% of the time grazing. The type of vegetation, forage availability and season normally affect foraging behavior of ruminants (Selemani et al. 2013b) as was displayed on the moderate bush plots where cows continued to spend 75% of the time grazing, while goats spent 70% of the time browsing. Free-ranging animals tend to trade-off between quality and quantity, taking into account the balance between energy gain and energy expenditure. Although the Optimal Foraging Model (OFM) predicts that animals tend to select the best forage species of highest nutritional value (Merritt Emlen 1966), constraints other than forage quality can limit animal selectivity (Feasta-Beanchet 1988). Forage availability can also affect foraging behavior independent of quality and therefore dietary overlap is more pronounced during acute shortage of forage (Selemani et al. 2013b).

Animal foraging behavior or perceptions of a resource pattern is largely determined by the relative consistency in assemblage of the plant populations (patchiness) that are clustered in response to soil type or pattern of disturbance (Senft et al. 1987). A patch is defined as spatial aggregation of bites over which instantaneous intake rate remains constant (Baumont et al. 2000). Variations in patch structure, nutritive value and species composition influence selectivity and amount of time animals spend within a particular patch. The significantly higher number of patches in thick bush and open grassland compared with moderate bush possibly reflects differences in nutritive value and vegetation structure. Both open grassland and thick bush most likely provided inadequate forage resources that forced foraging animals to select many patches to satisfy their nutritional requirements. For example, open grassland was dominated by grasses such as *Urochloa mosambicensis*, *Bothriochloa pertusa*, *Cynodon nlemfuensis* and *Hyparrhenia* spp., which naturally tend to have low digestibility and low crude protein at the end of the short dry season. Mwilawa et al. (2008) pointed out that in semi-arid regions natural pastures are characterized by low nutritional value when mature, which native species normally achieve very rapidly. On the other hand, higher numbers of patches in thick bush could be attributed to poor accessibility and tree maturity. There is growing evidence that diet selection is largely regulated by physical structure rather than nutritive value of particular tree species (Bryant et al. 1991). The thick bush was colonized mainly by *Acacia* spp. with defensive thorns and spines. According to Rooke (2003), more closely spaced thorns and spines restrict movement of animals and hence reduce accessibility of forage. Therefore the lower number of bites in thick bush as established in the current study might be associated with plant physical attributes rather than chemical defense mechanisms because higher concentrations of secondary compounds are more pronounced in younger shoots than in mature ones (Rooke 2003), which would be the case in moderate bush.

The higher preference for woody vegetation shown by dairy goats over dairy cows has also been observed in other studies (Celaya et al. 2007; Selemani et al. 2013b). In addition, goats spent little time browsing within a single patch and tended to move quickly to the next patch, especially on open grassland and thick bush. According to the OFM, differences in foraging abilities among animals are a result of natural selection (MacArthur and Pianka 1966; Merritt Emlen 1966; Pyke 1984). Goats have significantly higher inherited foraging ability than cattle and are more efficient at selecting a high quality diet and maximizing energy intake within a high quality patch or landscape (Gordon 2003; Goetsch et al. 2010). Goats probably maximized bite rate in moderate bush in preference to other subplots due to availability of high quality browse as discussed earlier. Goats are able to survive harsh conditions due to their unique dietary selection (Pfister and Malechek 1986), as there is a close relationship between foraging behavior and survival fitness (Pyke 1984). Survivability of goats is a function of their high ability to select from within available forage and to utilize a wide range of ecological habitats.

Conclusions and Recommendations

The study has shown that the degree of bush encroachment had a significant influence on foraging behavior of dairy cows and goats. Transformation of grassland to woodland created sub-habitats which differ from open grassland, and total time spent grazing plus browsing by dairy cows was reduced by about 12% on areas with significant bush encroachment. Interestingly, time devoted to browsing in each case remained constant at about 25% of total time devoted to browsing plus grazing. Unless the quality and quantity of forage available on the different treatments varied markedly, production levels might be expected to decline slightly on bush areas for cows. On the other hand foraging behavior of goats changed dramatically as amount of bush encroachment increased. Depending on the quality and quantity of browse available, production could be affected considerably by level of bush encroachment. In the absence of information on effects of different bush encroachment levels on performance of the two species, it is not possible to state whether or not cows should preferentially be run on grassland and goats on areas invaded by shrubs. Studies are needed not only to determine what impacts there might be on production levels from the various treatments but also to measure availability of herbage and browse on the different treatments as both quantity and quality affect performance. As both goats and dairy cows lactate, it would be easy to measure milk yields since are highly sensitive to feed intake. Further studies are needed to provide information on these particular aspects and also how patterns might change with the various seasons and availability and quality of grass/herbage versus browse differs. Further studies on nutritional composition and phytochemical analysis of key forage species in the study area are recommended.

Acknowledgments

The author is grateful to the Department of Animal, Aquaculture and Range Science for providing permission to conduct the experiment at Magadu Dairy Farm. Many thanks also go to Mr. Msangi Ikamba and Mr. Mmken Ibrahim for their assistance during data collection.

References

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

Adler PB; Raff DA; Lauenroth WK. 2001. The effect of grazing on the spatial heterogeneity of vegetation. Oecologia 128:465–479. DOI: 10.1007/s004420100737

Bailey DW; Gross JE; Laca EA; Rittenhouse LR; Coughenour MB; Swift DM; Sims PL. 1996. Mechanisms that result in large herbivore grazing distribution patterns. Journal of Range Management 49:386–400. DOI: 10.2307/4002919

Baumont R; Prache S; Meuret M; Morand-Fehr P. 2000. How forage characteristics influence behaviour and intake in small ruminants: A review. Livestock Production Science 64:15–28. DOI: 10.1016/S0301-6226(00)00172-X

Britz ML; Ward D. 2007. Dynamics of woody vegetation in a semi-arid savanna, with a focus on bush encroachment. African Journal of Range and Forage Science 24:131–140. DOI: 10.2989/ajrfs.2007.24.3.3.296

Bryant JP; Provenza FD; Pastor J; Reichardt PB; Clausen TP; du Toit JT. 1991. Interaction between woody plants and browsing mammals mediated by secondary metabolites. Annual Review of Ecology and Systematics 22:431–446. DOI: 10.1146/annurev.es.22.110191.002243

Celaya R; Olivan M; Ferreira LMM; Martinez A; Garcia U; Osoro K. 2007. Comparison of grazing behaviour, dietary overlap and performance in non-lactating domestic ruminants grazing on marginal heathland areas. Livestock Science 106:271–281. DOI: 10.1016/j.livsci.2006.08.013

Cottam G; Curtis JT. 1956. The use of distance measures in phytosociological sampling. Ecology 37:451–460. DOI: 10.2307/1930167

Coughenour MB. 1991. Spatial components of plant-herbivore interactions in pastoral, ranching and native ungulate ecosystems. Journal of Range Management 44:530–542. DOI: 10.2307/4003033

Feasta-Beanchet M. 1988. Seasonal range selection in bighorn sheep: Conflicts between forage quality, quantity and predator avoidance. Oecologia 75:580–586. DOI: 10.1007/bf00776423

Goetsch AL; Gipson TA; Askar AR; Puchala R. 2010. Invited review: Feeding behavior of goats. Journal of Animal Science 88:361–373. DOI: 10.2527/jas.2009-2332

Gordon IJ. 2003. Browsing and grazing ruminants: Are they different beasts? Forest Ecology and Management 181:13–21. DOI: 10.1016/s0378-1127(03)00124-5

Gowing JW; Palmer M. 2008. Sustainable agricultural development in sub-Saharan Africa: The case for a paradigm shift in land husbandry. Soil Use and Management 24:92–99. DOI: 10.1111/j.1475-2743.2007.00137.x

Illius AW; Gordon IJ; Elston DA; Mjlne JD. 1999. Diet selection in goats: A test of intake-rate maximization. Ecology 80:1008–1018. DOI: 10.2307/177034

Kambatuku JR; Cramer MD; Ward D. 2010. Savanna tree–grass competition is modified by substrate type and herbivory. Journal of Vegetation Science 22:225–237. DOI: 10.1111/j.1654-1103.2010.01239.x

Kizima JB; Mtengeti EJ; Nchimbi-Msolla S. 2014. Seed yield and vegetation characteristics of *Cenchrus ciliaris* as influenced by fertilizer levels, row spacing, cutting height and season. Livestock Research for Rural Development 26, Article #148. goo.gl/GSYf5W

MacArthur RH; Pianka ER. 1966. On optimal use of a patchy environment. The American Naturalist 100:603–609. DOI: 10.1086/282454

Martin P; Bateson P. 2007. Measuring behavior: An introductory guide. 3rd Edn. Cambridge University Press, New York, USA. DOI: /10.1017/CBO9780511810893

Merritt Emlen J. 1966. The role of time and energy in food preferences. The American Naturalist 100:611–617. DOI: 10.1086/282455

Mitchell K. 2007. Quantitative analysis by the point-centered quarter method. arxiv.org/abs/1010.3303

MLFD (Ministry of Livestock and Fisheries Development). 2015. Tanzania livestock modernization initiative 2015. MLFD, Dar es Salaam, Tanzania. hdl.handle.net/10568/67749

Moleele N. 1998. Encroacher woody plant browses as feed for cattle. Cattle diet composition for three seasons at Olifants Drift, south-east Botswana. Journal of Arid Environments 40:255–268. DOI: 10.1006/jare.1998.0450

Montgomery DC. 2001. Design and analysis of experiments, International Student Version. Wiley Inc., New York, USA.

Mwilawa AJ; Komwihangilo DM; Kusekwa ML. 2008. Conservation of forage resources for increasing livestock

production in traditional forage reserves in Tanzania. African Journal of Ecology 46:85–89. DOI: 10.1111/j.1365-2028.2008.00934.x
Njombe AP; Msanga Y; Mbwambo N; Makembe N. 2011. The Tanzania dairy industry: Status, opportunities and prospects. Paper presented to the 7th African Dairy Conference and Exhibition, Dar es Salaam, Tanzania, 25–27 May 2011. goo.gl/s57yFP
O'Connor TG; Chamane SC. 2012. Bush clump succession in grassland in the Kei Road region of the Eastern Cape, South Africa. African Journal of Range & Forage Science 29:133–146. DOI: 10.2989/10220119.2012.744776
Paavola J. 2008. Livelihoods, vulnerability and adaptation to climate change in the Morogoro region, Tanzania. Environmental Science & Policy 11:642–654. DOI: 10.1016/j.envsci.2008.06.002
Pfister JA; Malechek JC. 1986. Dietary selection by goats and sheep in a deciduous woodland of northeastern Brazil. Journal of Range Management 39:24–28. DOI: 10.2307/3899680
Pyke GH. 1984. Optimal foraging theory: A critical review. Annual Review of Ecology and Systematics 15:523–575. DOI: 10.1146/annurev.ecolsys.15.1.523
Rooke T. 2003. Growth responses of a woody species to clipping and goat saliva. African Journal of Ecology 41:324–328. DOI: 10.1111/j.1365-2028.2003.00478.x
SAS. 2004. SAS/STAT. User's guide. SAS Institute Inc., Cary, NC, USA.
Selemani IS; Eik LO; Holand Ø; Ådnøy T; Mtengeti E; Mushi D. 2013a. The effects of a deferred grazing system on rangeland vegetation in a north-western, semi-arid region of Tanzania. African Journal of Range & Forage Science 30:141–148. DOI: 10.2989/10220119.2013.827739
Selemani IS; Eik LO; Holand Ø; Ådnøy T; Mtengeti E; Mushi D. 2013b. Variation in quantity and quality of native forages and grazing behavior of cattle and goats in Tanzania. Livestock Science 157:173–183. DOI: 10.1016/j.livsci.2013.08.002
Senft RL; Coughenour MB; Bailey DW; Rittenhouse LR; Sala OE; Swift DM. 1987. Large herbivore foraging and ecological hierarchies: Landscape ecology can enhance traditional foraging theory. Bioscience 37:789–798. DOI: 10.2307/1310545
Tefera S; Snyman HA; Smit GN. 2007. Rangeland dynamics of southern Ethiopia: (2). Assessment of woody vegetation structure in relation to land use and distance from water in semi-arid Borana rangelands. Journal of Environmental Management 85:443–452. DOI: 10.1016/j.jenvman.2006.10.008
Thomas DSG; Twyman YC. 2004. Good or bad rangeland? Hybrid knowledge, science, and local understandings of vegetation dynamics in the Kalahari. Land Degradation & Development 15:215–231. DOI: 10.1002/ldr.610
Vermeire LT; Mitchell RB; Fuhlendorf SD; Gillan RL. 2004. Patch burning effects on grazing distribution. Journal of Range Management 57:248–252. DOI: 10.2458/azu_jrm_v57i3_vermeire
Volpato GH; Martins SV; Carvalho J; Anjos L dos. 2010. Accuracy and efficiency evaluation of point-centered quarter method variations for vegetation sampling in an *Araucaria* forest. Revista Árvore 34:513–520. DOI: 10.1590/s0100-67622010000300015
Ward D. 2005. Do we understand the causes of bush encroachment in African savannas? African Journal of Range & Forage Science 22:101–105. DOI: 10.2989/10220110509485867
Wiskerke WT; Dornburg V; Rubanza CDK; Malimbwi RE; Faaij APC. 2010. Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania. Renewable and Sustainable Energy Reviews 14:148–165. DOI: 10.1016/j.rser.2009.06.001

(Received for publication 18 August 2017; accepted 14 June 2018; published 30 September 2018)