Boshrabadi, H., Villano, R. and Fleming, E., 2008. Technical efficiency and environmental technological gaps in wheat production in Kerman province of Iran. *Agricultural Economics*, 38(1):67-76.

Brummer, B., Loy, J.P., 2000. The technical efficiency impact of farm credit programmes: A case study in Northern Germany. Journal of Agricultural Economics, 51(3), 405-418.

Chen, X., Ender, P., Mitchell, M. and Wells, C., 2003. Regression with Stata. Available from http://www.ats.ucla.edu/stat/stata/webbooks/reg/default.htm [Last accessed: 29 October 2014].

Chen, Z. and Song S., 2008. Efficiency and technology gap in China's agriculture: A regional metafrontier analysis. *China Economic Review*, 19(2):287-296.

Coelli, T. J., 1995. 'Estimators and hypothesis tests for a stochastic frontier function: A Monte Carlo analysis', Journal of Productivity Analysis, 6(3):247 – 268.

Coelli, T. J., 1996. A guide to Frontier version 4.1: A computer program for stochastic frontier production and cost function estimation. CEPA Working Papers 7/96. Department of Econometrics, University of New England, Armidale, New South Wales, Australia.

Coelli, T., Rao, D. S. P., Battese, G. E., 2005. *An Introduction to Efficiency and Productivity Analysis*, second edition, Kluwer Academic Publishers, Boston.

Delgado, C.L., Narrod, C.A.,Tiongco, M.M., de Camargo Barros, G.S.A., 2008. Determinants and Implications of the growing scale of Livestock farms in four fast-growing Developing Countries. International Food Policy Research Institute, Washington, DC

Diagne, A., 2010. Technological change in smallholder agriculture: Bridging the adoption gap by understanding its source. *African Journal of Agricultural and Resource Economics* 5(1), 261-286.

Farrell, M. J., 1957. The measurement of productive efficiency', *Journal of Royal Statistical Society, Series A (general)*, **120**(3):253-281.

Food and Agriculture Organisation (FAO) and Ministry of Agriculture (MoA), 2013. Botswana Agrifood Value Chain Project: Beef Value Chain Study. Rome, Italy and Gaborone, Botswana.

Gaspar, P., Mesias, F. J., Escribano, M. and Pulido, F., 2009. Assessing the technical efficiency of extensive livestock farming systems in Extremadura, Spain. *Livestock Science*, 121(1):7-14.

Greene, W. H., 2003. *Econometric Analysis*, fifth edition, ISBN: 0-13-110849-2, Prentice Hall, New York.

Hachigonta, S., G. C. Nelson, T. S. Thomas, and L. Sibanda, eds. 2013. Southern African Agriculture and Climate Change: A Comprehensive Analysis. Washington, DC: International Food Policy Research Institute.

Hadley, D., 2006. Patterns in technical efficiency and technical change at the farm-level in England and Wales, 1982-2002. *Journal of Agricultural Economics*, 57(1):81-100.

Hamza, K., Rich, K. M., Baker, D., Bahta, S., and Katjiuongua, H., 2014. An Analysis of Beef Market Liberalization in Botswana: A Quantitative Value Chain. Selected paper for presention at the International Food and Agribusiness Management Association Annual Meetings, June 16-17, 2014, Cape Town, South Africa.

Hayami, Y. and Ruttan, V. W., 1970. Agricultural productivity differences among countries. *American Economic Review*, 60(5):895-911.

Kodde, D.A., Palm, F.C., 1986. Wald Criteria for Jointly Testing Equality and Inequality Restrictions. *Econometrica*, 54,243-1248.

Lapar, A.L. Ma., Garcia, A., Aditto, S., Suriya, P., 2005. Measuring cost efficiency in smallholder dairy: empirical evidence from Northeast Thailand. Selected paper for presentation at American Agricultural Economics Association Annual Meeting. Providence, Rhode Island. July 24-27, 2005.

MacDonald, J., Perry, J., Ahearn, M., Banker, D., Chambers, W., Dimitri, C., Key, N., Nelson, K. and Southard, L., 2004. Contracts, Markets and Prices: Organizing the Production and Use of Agricultural

Commodities. *Agricultural Economic report No. 837*, Economic Research Service, United States Department of Agriculture (USDA), Washington DC. Available from: www.ers.usda.gov [Last accessed: 22 October, 2014].

Mathijs, E., Vranken, L., 2001. Human capital, gender and organisation in transition agriculture: Measuring and explaining technical efficiency of Bulgarian and Hungarian farms. Post-Communist Economies, 13(2), -171-187.

Ministry of Finance and Development Planning (MFDP), 2009. National Development Plan 10, MFDP, Gaborone.

O'Donnell, C.J., Rao, D.S.P., Battese, G.E., 2008. Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. *Empirical Economics* 34(2), 231-255.

Otieno, D.J., Hubbard, L., Ruto, E., 2012. Determinants of technical efficiency in beef cattle production in Kenya. Selected paper prepared for presentation at the International Association of Agricultural Economists (IAAE) Triennial Conference, Foz do Iguacu, Brazil, 18-24 August, 2012.

Pascoe, S., Tingley, D. and Mardle, S. (Eds)., 2003. Multi-output measures of technical efficiency in EU fisheries. CEMARE Report 62, CEMARE, University of Portsmouth, UK.

Rakipova, A.N., Gillespie, J.M. and Franke, D.E., 2003. Determinants of technical efficiency in Louisiana beef cattle production. *Journal of ASFMRA*. Research and Case Studies, 99-107.

Staal, S.J., 2002. The competitiveness of smallholder dairy production: Evidence from Sub-Sahara Africa, Asia and Latin America. In Rangnekar, D. and Thorpe, W. (Eds, 2002.Smallholder dairy production and marketing opportunities and constraints. Proceedings of a South-South Workshop held at NDDB, Anad, India, 13-16 March 2001. NDDB (National Dairy Development Board, Anad, India and ILRI (International Livestock Research Institute) Nairobi, Kenya.538 pp.

StataCorp. 2009. *Stata Statistical Software: Release 11*. College Station, TX: StataCorp LP.

Statistics Botswana, 2014. Annual Agricultural Survey. Preliminary Results No. 19 of 2013. Gaborone, Botswana.

Tsionas, E. G., 2002. Stochastic frontier models with random coefficients. *Journal of Applied Econometrics*, 17(2):127-147.

Villano, R., Boshrabadi, H. M. and Fleming, E., 2010. 'When is metafrontier analysis appropriate? An example of varietal differences in Pistachio production in Iran. *Journal of Agricultural Science and Technology*, 12(4):379-389.

Whistler, D., White, K. J. and Bates, D., 2007. SHAZAM Econometrics Software and User's Reference Manual Version 10. Northwest Econometrics, Ltd., Vancouver. Available from: http://shazam.econ.ubc.ca/ [Last accessed: 29 October 2014].

Wollny, C. B. A., 2003. The need to conserve farm animal genetic resources in Africa: Should policy makers be concerned? *Ecological Economics*, 45(3):341-351.

Wooldridge, J. M., 2002. *Econometric Analysis of Cross Section and Panel Data*, MIT Press, Massachusetts.

Yahoo Finance, 2013. Available from: http://finance.yahoo.com [Last accessed: 29 October, 2013].

Appendix 1

Note:

Due to measurement difficulties, this study follows the revenue approach recently applied in the literature (Hadley, 2006; Abdulai and Tietje, 2007; Gaspar *et al*., 2009) and defines output as:

$$Q_{i(j)} = \frac{\sum_r^R yP}{t} \quad (1)$$

where $Q_{i(j)}$ is the annual value of beef cattle output of the ith farm in the j^{th} region (measured in Botswana Pula[10]); *r* denotes any of the three forms of cattle output considered, i.e., current stock, sales or uses for other purposes in the past twelve-month period; *y* is the number of beef cattle equivalents[11]; *p* is the current price of existing stock or average price for cattle sold/used during the past twelve months; and *t* is the average maturity period for beef cattle in Botswana, which based on expert consultation is assumed to be four years.

Similarly, to ensure that the study captures the approximate share of feeds from different sources in each beef region, the quantities of purchased and non-purchased (on-farm) feeds were first adjusted in accordance with the average annual number of dry and wet months[12], respectively, in the country.

Average feed prices were computed using the survey's price information collected for purchased feed with further validation by animal nutrition experts in the Department of Agricultural Research (DAR). Both purchased and non-purchased feeds were then converted to improved feed equivalents by multiplying the respective feed quantities by the ratio of their prices (or shadow prices) to the average per unit price of improved fodder.

Thus, following Otieno (2011), the total annual improved feed equivalent was computed as:

$$\{\varphi(p_f * d) + S(n_p * w)\} \quad (2)$$

Where; φ and S denote, respectively, the ratio of prices of purchased and non-purchased feed to that of improved fodder; p_f and n_p represent the average quantities of purchased and non-purchased feeds, respectively, in kilograms per month; *d* is the approximate number of dry months (when purchased feeds are mainly used), while *w* is the length of the wet season (when farmers mostly use on-farm or non-purchased feeds) in a particular area.

Depreciation costs on fixed inputs were based on the straight line method, using useful economic life farm equipment provided by each farm household. Labor costs comprise both paid and unpaid labor; the latter valued using the average minimum farm wage in a particular district. The labor costs were adjusted with the share of cattle income in household income. Similar adjustments were applied to other incidental variable costs, such as fuel and electricity bills.

To ensure consistent estimates of inefficiency effects in the SFA, a one-stage model is used, as proposed by Battese and Coelli (1995). In estimating the SFA both Cobb-Douglas and Translog production models were tested to test the model's fit to the survey data.

A likelihood ratio test showed that the Cobb-Douglas functional form provided a better fit to the survey data than a translog model[13.]

[10] One Botswana Pula is on average 0.1261 USD (Yahoo Finance (2013).

[11] Following (Otieno, 2012; Hayami and Ruttan., 1970; O'Donnell et al., 2008). Beef cattle equivalents were computed by multiplying the number of cattle of various types by conversion factors. Following insights from discussions with BMC (Botswana Meat Commission), the conversion factors were calculated as the ratio of average slaughter weight of different cattle types to the average slaughter weight of a mature beef bull. The average slaughter weight of mature bull, considered to be suitable for beef in Botswana, is between 452-500kg. according to BMC, the average slaughter weights for castrated adult males (oxen>3 years), Immature males (< 3 years), Cows (calved at least once), Heifers(female ≥1yr,have not calved), Male calves (between 8 weeks&<1year),Female calves (between 8 weeks&<1year), , Pre weaning males (<8 weeks), Pre weaning females (<8 weeks) are 400kg, 350kg, 390kg,300kg,250kg, 220kg,95kg and 95 kg, respectively. The calculated average slaughter conversion factors were then: 1.0, 0.86, 0.76, 0.84, 0.65, 0.48, 0.54,0.21 and 0.21, for Bulls, castrated adult males, Immature males , Cows, heifers, Male calves, Female calves, Pre weaning males and Pre weaning females, respectively

[12] Botswana is an arid country and according experts information the length of the wet season when farmers mostly use on-farm or non-purchased feeds do not exceed 5 months. Consequently, the study uses 5 wet and 7 dry months, respectively.

[13] Following Battese et al (2004), the likelihood ratio (LR) statistic calculated as : -2{ln[L(Ho)]- ln[L(H1)]} where ln[L(Ho) and ln[L(H1)] are values of the log likelihood function for the Cobb-Douglas and translog models, respectively. The test fails to reject the null hypothesis that Cobb-Douglas model is a better specification of sample data, with a LR statistic of 59.12 compared to the chi-square critical value of 11.38 at 10% and 7 degrees of freedom. Degrees of freedom equal the difference in the number of parameters estimated in the two models.

All the parameters in the proposed stochastic frontier and technical inefficiency effects model were estimated simultaneously in the equation:

$$lnQ_{i(j)} = \beta_{0(j)} + \sum_{r=1}^{4} \beta_{r(j)} lnX_{ir(j)} - M_i\delta_j + v_{i(j)} \quad (3)$$

Where $Q_{i(j)}$ is the annual value of beef cattle output of the i[th] farm in the j[th] region and measured as indicated in (16). X_{ir} represents a vector of inputs where X_{i1} is total feed equivalents, X_{i2} denotes the cost of veterinary services, and X_{i3} is the cost labor, while X_{i4} is a Divisia index calculated as (Boshrabadi et al., 2008)[14]:

$$X_{i4} = \Pi_{r=1}^{2} C_{ir(j)}^{\propto_{ir}} \quad (4)$$

Where $\alpha_{ir(j)}$ represents the share of the n[th] input in the total cost for the i[th] farm in the j[th] region; $C_{i1(j)}$ is the depreciation; insurance and taxes on farm buildings, machinery and equipment (Pula); $C_{i2(j)}$ represents other overhead costs including fuel, electricity, market services, maintenance costs, branding etc., in Pula terms.

M denotes the vector of socio-demographic and other independent variables assumed to influence efficiency; *v* represents statistical noise and δ is a vector of inefficiency parameters to be estimated.

Intuitively, a positive sign of the coefficient of efficiency driver variable (δ) implies inefficiency because the value of u (u=Mδ) would be higher when the farm is farther away below the frontier. On the contrary, a negative sign of the coefficient is interpreted as potentially having a positive influence on efficiency (Brummer and Loy, 2000; Coelli et al., 2005; Delgadoet al. 2008; Otieno et al. 2012).

The parameters of the stochastic frontiers were obtained by using FRONTIER 4.1 software (Coelli, 1996). The linear programming, to estimate meta-frontier (Equation 8), and bootstrapping of standard errors were undertaken in SHAZAM version 10 (Whistler *et al*., 2007), while STATA version 11 (StataCorp, 2009) was used for the Tobit analysis (Equation 13).

Appendixe 2

Average annual output and inputs

Variables	South East (N=219)	Central (N=200)	Chobe (N=149)	Pooled sample (N=568)
Value of beef cattle output (Pula)	17614[c]	47366[a]	28893[b]	31,048
Veterinary costs (Pula)	449[b]	619[a]	505[a]	524
Paid labor costs (Pula)	8693[a]	6862[c]	7951[b]	7854
Purchased feed equivalents (Kg)	399[a]	404[a]	277[b]	370
On-farm feed equivalents (Kg)	377[b]	815[a]	228[c]	492
Depreciation costs (Pula)	2591[b]	5331[a]	4923[a]	4168
Cost of other inputs (Pula)	2189[b]	5715[a]	4866[a]	4134

Notes: [a,b,c] differences in the superscripts represent significant differences (at 10% level or better) across the regions. Total labor costs and feed equivalents comprise both paid and unpaid labor, and purchased and on-farm feeds, respectively.

[14] The Divisia index is a proxy variable used to consolidate inputs such as depreciation and other costs so that to improve the model fit. All input costs are adjusted with the share of cattle income in household income.