**Supplementary material**

**The greenhouse gas abatement potential of productivity improving measures applied to cattle systems in a developing region**

G. R. Salmon1, 2, K. Marshall3, S. F. Tebug3, A. Missohou4, T. Robinson5,and M. MacLeod1

1*SRUC, West Mains Road, Edinburgh, EH9 3JG, UK*

2*The University of Edinburgh, King’s Buildings, West Mains Road, Edinburgh EH9 3JN, UK*

3*The International Livestock Research Institute, PO 30709, Nairobi 00100, Kenya*

4*Inter-State School of Veterinary Science and Medicine (EISMV), Dakar, Senegal*

5*FAO-AGAL, Viale delle Terme di Caracalla, 00153 Rome, Italy*

Corresponding author: Gareth Salmon. Email: gareth.salmon@sruc.ac.uk



Figure S1 *Summary of the calculation of emissions intensity for protein production (kgCO2eq/kg protein) within the version of GLEAM used in this study. Bold italicised text indicates model user inputs. Dashed boxes indicate the emission categories included in the assessment. NE - net energy, GE - gross energy, CH4 - methane, N2O - nitrous oxide, CO2 - carbon dioxide, N - nitrogen. For more information, see Food and Agriculture Organization of the United Nations (2017).*

Table S1 *Model input parameters, assumptions and source information defining baseline systems. ‘+’ refers to levels of management, see main text for details of this.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Model parameters | Unit information | IZ | IZ x GZ | IZ x BT | BT | Explanation/source information |
| + | ++ | + | ++ | ++ | +++ | ++++ |
| *Animal productivity* |  |  |  |  |  |  |  |  |
| Adult female weight | kg | 294.4 | 316.8 | 301.7 | 309.2 | 333.3 | 413.6 | 432.6 | SDG |
| Calf weight at birth | kg | 20.6 | 22.2 | 21.1 | 21.6 | 23.3 | 29.0 | 30.3 | SDG |
| Milk offtake | kg/year/lactating cow | 323.4 | 876.9 | 411.0 | 988.8 | 937.1 | 2 032.1 | 2 196.8 | SDG |
| Milk suckled | kg/year/lactating cow | 516.2 | 516.1 | 463.6 | 463.6 | 511.4 | 511.4 | 488.6 | SDG |
| Milk fat content | % by mass | 4.9 | 4.9 | 5.1 | 5.1 | 5.1 | 5.1 | 5.8 | Ema *et al.* (2014) |
| Milk protein content | % by mass | 3.7 | 3.7 | 3.7 | 3.7 | 3.5 | 3.5 | 3.7 | Ema et al. (2014) |
| Age at first calving | years | 4.3 | 3.8 | 3.7 | 3.7 | 3.5 | 3.5 | 3.3 | SDG |
| Fertility rate adult females | proportion giving birth/year | 0.57 | 0.63 | 0.55 | 0.71 | 0.55 | 0.71 | 0.63 | SDG |
| Death rate at birth | proportion dying at birth/1st week | 0.04 | 0.04 | 0.14 | 0.14 | 0.04 | 0.04 | 0.08 | SDG |
| Death rate female calves (0-1) | proportion dying aged 0-1 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.07 | SDG |
| Death rate male calves (0-1) | proportion dying aged 0-1 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | SDG |
| Death rate young animals (1-2) | proportion dying aged 1-2 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.06 | SDG |
| Death rate young animals (2-3) | proportion dying aged 2-3 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.06 | SDG |
| Death rate adult females | proportion dying/year | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.07 | SDG |
| Death rate adult males (AFC - death) | proportion dying/year | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | SDG |
| Offtake young males age 0-1 | proportion sold /year | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | SDG |
| Offtake young males age 1-2 | proportion sold /year | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | SDG |
| Offtake young males age 2-3 | proportion sold /year | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | SDG |
| Offtake young females age 0-1 | proportion sold /year | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | SDG |
| Offtake young females age 1-2 | proportion sold /year | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | SDG |
| Offtake young females age 2-3 | proportion sold /year | 0.16 | 0.36 | 0.17 | 0.30 | 0.25 | 0.36 | 0.26 | SDG |
| Offtake adult females | proportion sold /year | 0.19 | 0.17 | 0.17 | 0.17 | 0.15 | 0.15 | 0.11 | SDG |
| Offtake adult males | proportion sold /year | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | SDG |
| *Herd information* |  |  |  |  |  |  |  |  |
| Adult female replacement rate | proportion of cows replaced/year | 0.21 | 0.19 | 0.19 | 0.19 | 0.18 | 0.18 | 0.18 | SDG |
| Bull:cow ratio |  | 0.25 | 0.30 | 0.22 | 0.27 | 0.25 | 0.30 | 0.28 | SDG |
| Labour | average hours of draft work/year | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | SDG |
| *Ration compositions and lifecycle information* |  |  |  |  |  |  |  |  |
| Maize grain | % of ration | 0.6 | 2.0 | 1.9 | 1.8 | 2.2 | 3.3 | 11.4 | SDG |
| Millet stover | % of ration | 10.1 | 10.0 | 11.6 | 10.9 | 7.3 | 3.1 | 15.4 | SDG |
| Bran | % of ration | 4.9 | 11.0 | 8.3 | 6.8 | 9.2 | 13.4 | 24.9 | SDG |
| Purchased compound feed (PC) | % of ration composed of PC | 3.6 | 9.1 | 7.7 | 8.1 | 8.9 | 16.5 | 32.0 | SDG |
| Groundnut cake | % of ration | 5.0 | 7.2 | 5.4 | 5.9 | 10.4 | 13.1 | 17.3 | SDG |
| Groundnut shells | % of ration | 0.4 | 1.1 | 0.9 | 1.0 | 1.0 | 1.8 | 3.5 | SDG |
| Senegal pasture | % of ration | 74.1 | 55.6 | 62.3 | 63.5 | 51.6 | 34.2 | 7.8 | SDG |
| Pasture (cut and carry) | % of ration | 1.0 | 3.6 | 1.2 | 1.6 | 3.2 | 5.9 | 2.7 | SDG |
| Senegal hay | % of ration | 3.9 | 9.5 | 8.5 | 8.5 | 14.9 | 25.2 | 17.0 | SDG |
| *Synthetic fertiliser application* |  |  |  |  |  |  |  |  |
| Maize grain | kgN/ha/year | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | Brazil import1; Richetti and Ceccon (2015) and FAO (2004) |
| Millet stover | kgN/ha/year | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | Sonneveld *et al.* (2016) and IFDC (2014) |
| Bran | kgN/ha/year | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | Sonneveld *et al.* (2016) and IFDC (2014) |
| Groundnut cake | kgN/ha/year | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | Sonneveld *et al.* (2016) and IFDC (2014) |
| Groundnut shells | kgN/ha/year | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | Sonneveld *et al.* (2016) and IFDC (2014) |
| Senegal pasture | kgN/ha/year | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Assumed zero |
| Pasture (cut and carry) | kgN/ha/year | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Assumed zero |
| Senegal hay | kgN/ha/year | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Assumed zero |
| *Manure fertiliser application* |  |  |  |  |  |  |  |  |
| Maize grain | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Millet stover | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Bran | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Groundnut cake | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Groundnut shells | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Senegal pasture | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Pasture (cut and carry) | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| Senegal hay | kgN/ha/year | 1.3 | 1.3 | 1.3 | 1.3 | 0.4 | 0.4 | 0.1 | Assumed, based on time spent confined |
| *Transport by land* |  |  |  |  |  |  |  |  |
| Maize grain | km | 1 364 | 1 364 | 1 364 | 1 364 | 1 364 | 1 364 | 1 364 | Brazil import1 |
| Millet stover | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Bran | km | 722 | 722 | 722 | 722 | 722 | 722 | 722 | Guinea & St. Louis import1 |
| Groundnut cake | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Groundnut shells | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Pasture (cut and carry) | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Senegal hay | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| *Transport by water* |  |  |  |  |  |  |  |  |
| Maize grain | km | 6 708 | 6 708 | 6 708 | 6 708 | 6 708 | 6 708 | 6 708 | Brazil import1 |
| Millet stover | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Bran | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Groundnut cake | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Groundnut shells | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Senegal pasture | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Pasture (cut and carry) | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| Senegal hay | km | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Local1 |
| *Ration materials gross yields harvested* |  |  |  |  |  |  |  |  |
| Maize grain | kgDM/ha/year | 1 119 | 1 119 | 1 119 | 1 119 | 1 119 | 1 119 | 1 119 | Brazil FAO STAT |
| Millet stover | kgDM/ha/year | 624 | 624 | 624 | 624 | 624 | 624 | 624 | Senegal FAO STAT |
| Bran | kgDM/ha/year | 1 151 | 1 151 | 1 151 | 1 151 | 1 151 | 1 151 | 1 151 | Senegal FAO STAT |
| Groundnut | kgDM/ha/year | 766 | 766 | 766 | 766 | 766 | 766 | 766 | Senegal FAO STAT |
| Senegal pasture | kgDM/ha/year | 498 | 498 | 498 | 498 | 498 | 498 | 498 | Sawadogo *et al.* (1999) |
| *Ration materials digestible energy* |  |  |  |  |  |  |  |  |
| Maize grain | DE%  | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | Feedipedia2 |
| Millet stover | DE% | 33.2 | 33.2 | 33.2 | 33.2 | 33.2 | 33.2 | 33.2 | Jarrige *et al.* (1989) |
| Bran | DE% | 73.0 | 73.0 | 73.0 | 73.0 | 73.0 | 73.0 | 73.0 | Feedipedia2 |
| Groundnut cake | DE% | 85.3 | 85.3 | 85.3 | 85.3 | 85.3 | 85.3 | 85.3 | Feedipedia2 |
| Groundnut shells | DE% | 15.8 | 15.8 | 15.8 | 15.8 | 15.8 | 15.8 | 15.8 | Jarrige *et al.* (1989) & Feedipedia2 |
| Senegal pasture | DE% | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | Jarrige *et al.* (1989) |
| Pasture (cut and carry) | DE% | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | 55.2 | Jarrige *et al.* (1989) |
| Senegal hay | DE% | 43.6 | 43.6 | 43.6 | 43.6 | 43.6 | 43.6 | 43.6 | Jarrige *et al.* (1989) |
| *Ration materials nitrogen content* |  |  |  |  |  |  |  |  |
| Maize grain | gN/kgDM | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | Feedipedia2 |
| Millet stover | gN/kgDM | 9.6 | 9.6 | 9.6 | 9.6 | 9.6 | 9.6 | 9.6 | Jarrige *et al.* (1989) |
| Bran | gN/kgDM | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 | Feedipedia2 |
| Groundnut cake | gN/kgDM | 78.4 | 78.4 | 78.4 | 78.4 | 78.4 | 78.4 | 78.4 | Feedipedia2 |
| Groundnut shells | gN/kgDM | 10.3 | 10.3 | 10.3 | 10.3 | 10.3 | 10.3 | 10.3 | Jarrige *et al.* (1989)& Feedipedia2 |
| Senegal pasture | gN/kgDM | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | Jarrige *et al.* (1989) |
| Pasture (cut and carry) | gN/kgDM | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | 14.8 | Jarrige *et al.* (1989) |
| Senegal hay | gN/kgDM | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | Jarrige *et al.* (1989) |

IZ = indigenous zebu; IZ x GZ = indigenous x Guzerat zebu cross; IZ x BT = indigenous zebu x taurine cross; BT = taurine; SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI); AFC = Age at first calving; DE% - Digestible energy as a proportion of gross energy

1Personal communication with Dr Cheikh Alioune Konate, Nutritionist for NMA Sanders feed merchants, Dakar. 6 May 2016; (Konate CA, 2016, personal communication)

2Feedipedia (2016)

Table S2 *Sensitivity analysis results, showing the percentage change in emissions intensity (kg CO2eq per kg protein) when individual input parameters are altered by -10% and +10%. Values shown are average across all seven defined herd types.*

|  |  |  |
| --- | --- | --- |
| Input parameter | -10% | +10% |
| Ration digestible energy | 25.07 | -16.95 |
| Milk yield | 6.02 | -5.28 |
| Adult female fertility rate | 6.02 | -4.78 |
| Adult female body weight | -2.99 | 2.80 |
| Age at first calving | -2.97 | 3.40 |
| Bull:cow ratio | -1.40 | 1.42 |
| Ration nitrogen content | -0.58 | 0.58 |
| Calf birth weight | 0.11 | 0.09 |
| Adult female replacement rate | -0.08 | 0.08 |
| Death rate (averaged across cohorts) | -0.01 | 0.01 |

Table S3 *Summary of mitigation measure shortlisting process*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Measure type | Mitigation measure shortlist (following literature review) | Comments from expert consultation | Mitigation measure shortlist (following expert consultation) | Comments from field visits | Mitigation measure (following field visits) |
|  |  |  |  |  |  |
| Diet & nutrition | Groundnut cake | Highly dependent on availability, but effective | Groundnut cake | Cost is a barrier for many farmers | Groundnut cake |
| Diet & nutrition | Effective concentrate feed supplementation | Quality is important. Effective supplementation can improve utilisation of poor quality forages | Effective concentrate feed supplementation | Cost is a barrier for many farmers | Effective concentrate feed supplementation |
| Diet & nutrition | Incorporation of legume crops into diet | Effective supplementation can improve utilisation of forages. There is contention between crop choices for human feed, cereals have more emphasis. | Incorporation of legume crops into diet | Competition for space and communal land access is a barrier for growing crops, which is currently unlikely to be resolved. | REMOVED |
| Diet & nutrition | Pasture & grazing management to improve quality (e.g. pasture age) | Communal use of pasture makes this problematic and unlikely to work. | Pasture & grazing management to improve quality (e.g. pasture age) | Competition for space and communal land access is a barrier, which is currently unlikely to be resolved | REMOVED |
| Diet & nutrition | Choice of straw type avoid low quality | Due to severe feed shortages, it is unlikely a choice between straw types can be made | REMOVED |  |  |
| Diet & nutrition | Chemical treatment of stovers (urea) | Highly effective, but rarely employed by farmers in SSA (due to labour, resources etc.) | Chemical treatment of stovers (urea) | The majority of study farmers positive. However barriers include: finance, resource, knowledge | Chemical treatment of stovers (urea) |
| Diet & nutrition | Make silage from fodder in wet season | Commonly storage problems; climate suites hay making. | Make silage from fodder in wet season | Most farmers say they are time, labour and resource limited |  |
| Diet & nutrition |  |  | Make hay at correct maturity for times of feed shortage | Most farmers say they are time and labour limited | Make hay at correct maturity for times of feed shortage |
| Animal health | Remove the burden of key diseases (to be identified) | Diseases primarily identified by farmer recall information (SDG data) | Lumpy skin disease | Understanding the prevalence and burden of specific diseases is challenging, farmers say vets are rare and expensive. Conversations with practicing vets confirmed shortlist | Lumpy skin disease |
| Foot and mouth disease | Foot and mouth disease |
| Trypanosomiasis | Trypanosomiasis |

Table S4 *Revenue and cost assumptions. ‘+’ refers to levels of management, see main text for details of this. All values are in Central African Franc (CFA), with approximate exchange rate 1CFA = 0.0016 USD*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | IZ | IZ x GZ | IZ x BT | BT |  |
|  |  | + | ++ | + | ++ | ++ | +++ | ++++ | Source |
| *Revenue sources* |  |  |  |  |  |  |  |  |  |
| Milk sale price  | per litre | 500 | 500 | 500 | 500 | 500 | 500 | 500 | SDG |
| Male calf sale price | per animal | 160 500 | 160 500 | 160 500 | 160 500 | 212 000 | 212 000 | 627 000 | SDG |
| Young male sale price | per animal | 176 000 | 176 000 | 205 500 | 205 500 | 536 000 | 536 000 | 933 000 | SDG |
| Mature male sale price | per animal | 261 500 | 261 500 | 385 500 | 385 500 | 434 000 | 434 000 | 800 000 | SDG |
| Young female sale price | per animal | 251 000 | 251 000 | 262 500 | 262 500 | 551 500 | 551 500 | 1 100 000 | SDG |
| Adult female sale price | per animal | 216 500 | 216 500 | 251 000 | 251 000 | 625 000 | 625 000 | 625 000 | SDG |
| *Baseline health costs* |  |  |  |  |  |  |  |  |  |
| Female calf health-care cost | per calf per annum | 120 | 244 | 198 | 287 | 444 | 459 | 573 | SDG |
| Male calf health-care cost | per calf per annum | 56 | 114 | 92 | 134 | 207 | 214 | 267 | SDG |
| Young male health-care cost  | per young per annum | 52 | 105 | 86 | 124 | 192 | 199 | 248 | SDG |
| Young female health-care cost | per young per annum | 106 | 215 | 175 | 253 | 392 | 405 | 506 | SDG |
| Mature male health-care cost  | per mature male per annum | 28 | 56 | 46 | 66 | 103 | 106 | 133 | SDG |
| Cow health-care cost | per cow per annum | 210 | 425 | 345 | 500 | 775 | 800 | 1 000 | SDG |
| *Baseline feed costs* |  |  |  |  |  |  |  |  |  |
| Male calf | per calf per annum | 12 500 | 33 000 | 19 500 | 35 500 | 36 000 | 65 500 | 123 500 | SDG |
| Young male  | per animal per annum | 34 500 | 90 000 | 53 500 | 98 500 | 99 000 | 175 000 | 330 500 | SDG |
| Mature male | per animal per annum | 55 500 | 138 000 | 81 000 | 149 000 | 145 500 | 258 500 | 473 500 | SDG |
| Female calf | per animal per annum | 9 000 | 24 500 | 14 500 | 26 500 | 27 000 | 49 000 | 92 000 | SDG |
| Female young  | per animal per annum | 25 000 | 65 500 | 39 000 | 71 500 | 71 500 | 127 000 | 239 500 | SDG |
| Cows | per animal per annum | 25 000 | 65 500 | 39 000 | 71 500 | 71 500 | 127 500 | 240 500 | SDG |
| Labour cost  | per herd per annum | 350 000 | 350 000 | 350 000 | 350 000 | 350 000 | 350 000 | 350 000 | SDG |
| Watering costs  | per herd per annum | 22 000 | 22 000 | 22 000 | 22 000 | 22 000 | 22 000 | 22 000 | SDG |
| *Additional feed costs* |  |  |  |  |  |  |  |  |  |
| groundnut cake | CFA/kg as purchased | 190 | 190 | 190 | 190 | 190 | 190 | 190 | SDG200400 studylling toconsidered. It is not enough to base local plans on /field visits |
| brans  | CFA/kg as purchased | 77 | 77 | 77 | 77 | 77 | 77 | 77 | SDG/ field visits |
| purchased compound feed | CFA/kg as purchased | 240 | 240 | 240 | 240 | 240 | 240 | 240 | SDG/ field visits |
| hay | CFA/kg as purchased | 11 | 11 | 11 | 11 | 11 | 11 | 11 | SDG/ field visits |
| *Additional health costs* |  |  |  |  |  |  |  |  |  |
| FMD Vaccine | CFA/dose | 50 | 50 | 50 | 50 | 50 | 50 | 50 | field visits |
| LSD vaccination | CFA/dose | 67 | 67 | 67 | 67 | 67 | 67 | 67 | field visits |
| Trypanocides | CFA/treatment | 500 | 500 | 500 | 500 | 500 | 500 | 500 | field visits |
| Antibiotic | CFA/treatment | 500 | 500 | 500 | 500 | 500 | 500 | 500 | field visits |

IZ = indigenous zebu; IZ x GZ = indigenous x Guzerat zebu cross; IZ x BT = indigenous zebu x taurine cross; BT = taurine; SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI); field visits = carried out by corresponding author May 2016

**Supplementary material references**

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