Upgrading the smallholder dairy value chain: a system dynamics ex-ante impact assessment in Tanzania's Kilosa district

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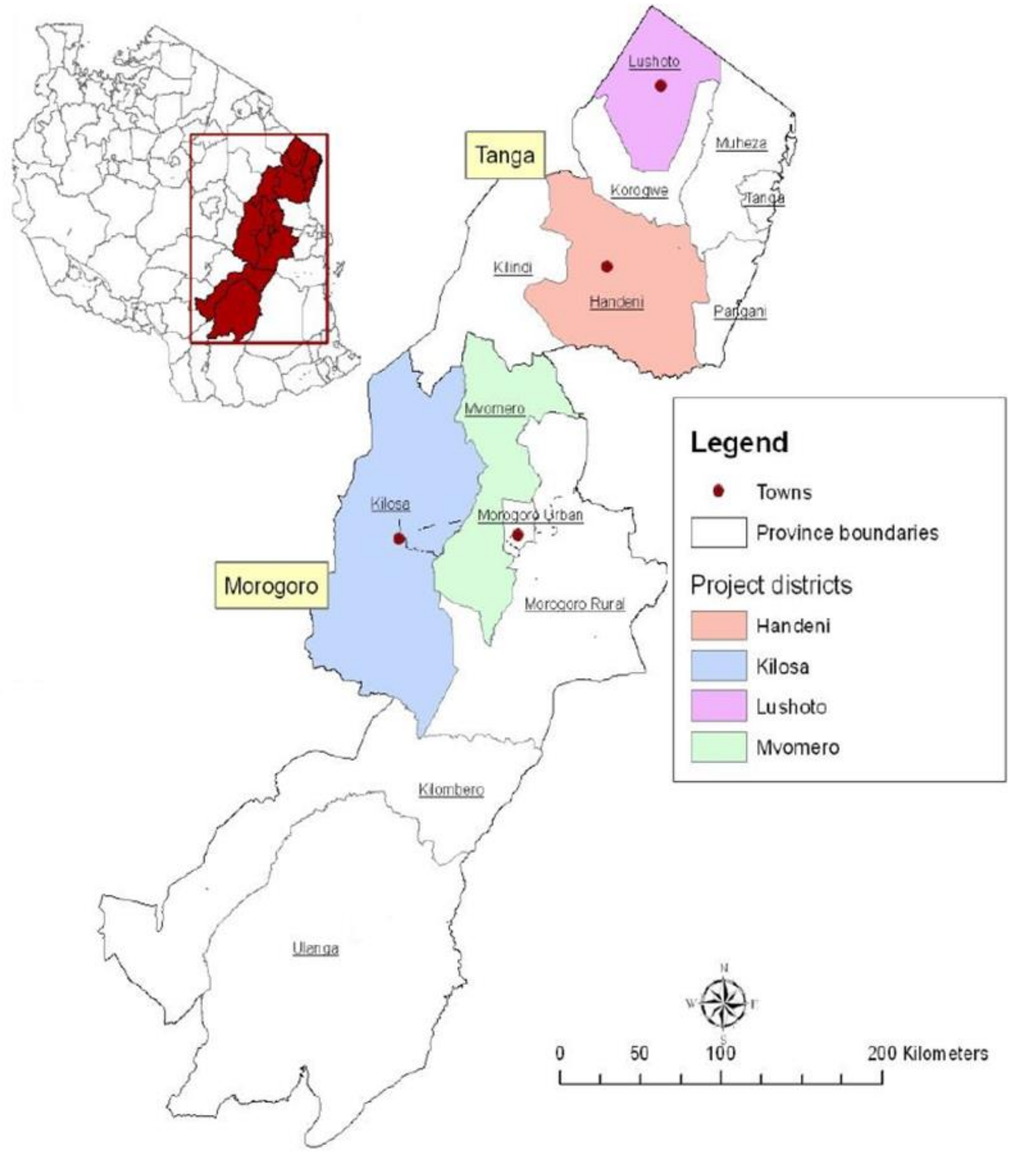
SUPPLEMENTARY FILE

SupplementaryTable S1: Main initial values and parameters used in the model

Initial Value	Value	Unit
Breeding Cows	1802	Cattle
Of which, Milk Producing Cows	800	Cattle
Calves	1256	Cattle
Pre-adult Male	443	Cattle
Pre-adult Female	1026	Cattle
Adult Male	674	Cattle
Production and stock management Parameters[1]		
Average fractional death rate (breeding cows)	5.3%	1/year
Average fractional death rate (calves)	5.3%	1/year
Average fractional death rate (pre-adult males)	5.3%	1/year
Average fractional death rate (pre-adult females)	5.3%	1/year
Average fractional death rate (adult males)	5.3%	1/year
Average Breeding period	416	Week
Gestation period	39	Week
Time to become pre-adults	52	Week
Time to Mature	130	Week
Lactation period	36	Week
Market Parameters	**Offtake rate**	
Average annual pre-adult male sales rate	9%	1/year
Average annual pre-adult female sales rate	1%	1/year
Average annual adult male sales rate	70%	1/year
Average annual breeding stock sales rate	0.2%	1/year s
Milk price (individual consumer)	0.48	USD/liter
Milk price (traders and collection centers)	0.4	USD/liter

(Source: ILRI (2014) – baseline data)

Supplementary Figure S1 Shows ILRI project study boundary and Kilosa district



Key:
R-to-R = Rural production milk sales mostly to rural consumers (pre-commercial)
R-to-U = Rural production milk sales mostly to urban consumers (more commercial)

Appendix 1: Producers cooperative and dairy market hub

Producers cooperative and organization is a collective action by a group of producers to access inputs and output markets that is not readily accessible for individual producers (Ouma & Abdulai, 2009). Shiferaw *et al*. (2016) highlighted the importance of producer organizations in enhancing access to output markets and agricultural technologies, and McRoberts *et al*. (2013) provided a case study of the role of a Mexican dairy cooperative in improving market access and household income in rural households. Fischer & Qaim (2014) discussed the benefits of producers' groups in enhancing market access, collective bargaining, and reducing transaction costs in Kenya's banana sector. Ouma *et al*. (2010) and Barrett (2008) emphasized producer groups' roles in addressing the constraints to smallholder participation in agricultural markets. In addition to improving market access by way of increased marketable volumes, livestock producer co-operatives have been shown also to enhance access to inputs such as breeding services (Abdelrahman & Smith, 1996; Ouma & Abdulai, 2009; Julius, 2015; Shiferaw *et al*., 2016). However, numerous cases demonstrate failure of co-operatives in such tasks (e.g. Zarafshani *et al*. (2010) in western Iran; Cazzuffi & Moradi (2010) in Ghana; Ortmann & King (2007) in South Africa; Abdelrahman & Smith (1996) in Western Sudan; and Jonathan & Kummburu (2016) in Tanzania).

There are calls for the reinstatement of co-operatives to intensify agricultural production and develop supply chains in Tanzania (Jonathan & Kummburu, 2016) and Africa more generally (Diao *et al*., 2010) to meet growing demand. Collective and co-operative action in dairy marketing and service delivery is widespread in developed countries, but the adapted dairy market hubs being promoted in Tanzania differ from cooperatives and larger farmer associations in their flexibility and informality of status (Twine & Omore, 2016). Smallholder dairy hubs largely facilitate and embody business linkages involving small scale milk traders; although a few are centered on milk chilling plants employing a variety of ownership models (farmer-, individual-, private- or processor-owned). A common feature of these diverse organizational forms is that their business linkages interweave input, output and service transactions so that farmers may access inputs or services on a deferred payment basis using their future milk delivery as collateral and as a means of repayment.

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Appendix 2: Model validation

We did not conduct a historic data replication test because of the lack of time series data from the study region. However, we conducted validation tests as suggested in Sterman (2000) and Forrester and Senge (1996) including structure assessment, dimension consistency, structure-behavior test, and extreme condition test.

Structure assessment: requires that the model structure does not include any components, variables and parameters that do not exist in real life. The model structure is consistent with physical real life system that the model represents.

Dimension consistency: requires that the model units are consistent without the use of any parameters that have no real life interpretation and meaning.

Structure-behavior test: requires that the model generates logical behavior when a feedback loop is cut from the model. For example, when the feedback loop of production (i.e. the connector between "breeding cows" and "breeding rate" in figure 2 is removed, the cattle population begins to decline because removing the connector between "breeding cows" and "breeding rate" cancels cattle breeding. That is, there will not be any reproduction.

Extreme condition test: Extreme condition tests were carried out for key parameters of the model. For example, forcing breeding stock to be zero (or disconnecting breeding stock from the rest of production cycle) or putting rainfall to extreme high or low values, the model behavior was realistic. Similarly, we conducted numerous parameter sensitivity tests, and model behavior was found to be realistic under all cases.

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Appendix 3: Sensitivity analysis

In this section, we report sensitivity analysis results of model outputs (baseline and policy intervention scenarios) in respect of +/- 20% (a uniform distribution is used) changes in milk price. We conducted 100-runs per scenario (baseline and policy interventions). We report results of performance indicators listed in table 4 (all tables presented in this paper show similar indicators). We first provide table A.1. in which we show outputs (general numbers) of each scenario), then we report sensitivity analysis results for model outputs of scenarios 1 (baseline), 2 (AI), and 3 (AI and market hub) in tables A.2., A.3., and A.4., respectively. Table A.1. shows cumulative outputs for each scenario by the end of simulation , 2035 – i.e. 20-year time. It should be noted that the values in this table are used to estimate the comparative figures of baseline and policy intervention scenarios reported in table 4 (above). In this section, we use this table to evaluate sensitivity of model outputs in respect of changes in milk price, and then report results for scenarios 1, 2 and 3 in tables A.2., A.3., and A.4. respectively. We report sensitivity analysis results in percentage figures: a mean of 100% means that, on average, the outcome of 100-runs (uniform distribution of +/- 20% of initial milk price) is the same as model outputs reported in table A.1. A value of more than 100% means higher magnitude results than the figures reported in table A.1., and vice versa. We also report median, standard deviation, minimum, and maximum figures.

Table A.1.: cumulative output - baseline and policy interventions - by the end of simulation, 2035

	Cumulative value by the end of simulation, 2035					
Scenarios*	**Milk production (liter)**	**Cumulative profit (USD)**	**Milk consumption** (liter)**	**Improved cross breed (%total population)**	**milk traded to market hub (liter)**	**Milk traded to processors (liter)**
Sce 1	8,395,183	580,619	5,199,900	0%	0	0
Sce 2	13,974,176	583,603	6,989,860	73%	0	0
Sce 3	13,187,901	1,354,633	6,749,864	67%	2,523,843	2,019,263

*Scenario1: Baseline; Scenario2: Artificial insemination; Scenario 2: Artificial Insemination + Market Hub
**Consumption includes consumption at producer households and given away (non-commercial).

Table A.2. shows sensitivity analysis results of model outputs under scenario 1 (baseline) – the row named Sce 1 in table A.1. As indicated in the sensitivity analysis section above, producers' cumulative profit is more sensitive to changes in milk price than are other performance indicators. The column labelled milk production shows that producers' total milk production, on average, equals 99% (median value equals 100%) of milk production value (i.e. 8,395,183 liter milk) of scenario 1 reported in table A.1. The standard deviation equals 2%, minimum 95% (i.e. 0.95*8,395,183), and maximum 102% (i.e. 1.02*8,395,183) of the reported value of milk production for scenario 1 in table A.1. Similar patterns are generated for the milk consumption variable. The sensitivity analysis of scenario 1 (baseline) shows that model outputs do not show substantial variability under different milk prices which indicated that the model output is robust, or not sensitive to changes in price.

Table A.2.: Sensitivity analysis results of scenario 1 (baseline)

Items	Milk production	Cumulative profit	Milk consumption	Improved cross breed (%total population)	milk traded to market hub (liter)	Milk traded to processors (liter)
Mean	99%	100%	99%	NA	NA	NA
Median	100%	100%	100%	NA	NA	NA
Standard Deviation	2%	26%	2%	NA	NA	NA
Minimum	95%	56%	95%	NA	NA	NA
Maximum	102%	145%	101%	NA	NA	NA

Tables A.3, and A.4, show sensitivity analysis results of scenario 2 (use of artificial insemination) and scenario 3 (AI and dairy market hub). A notable difference between sensitivity results of scenario 1 (baseline) and policy intervention scenarios (scenario 3 and, to a lesser extent, scenario 2) is that producers' cumulative profit (and other indicators) in policy intervention scenarios is less sensitive to changes in milk price. Indeed, sensitivity analysis output (100-run of uniform distribution of +/- 20% of milk price) showed that the mean, or average, of producers cumulative profit is 101% of cumulative profit (583,603 USD) of scenario 2 – reported in figure A.1.). This difference is observed because scenario 2 includes higher milk production due to using artificial insemination to improve genetic potential of cows which makes producers' profits less sensitive to changes in milk price. Sensitivity analysis outputs of producers' cumulative profit (mean = 101%; standard deviation = 15%, see table A.4. for more details) in scenario 3 is less sensitive than scenario 2 because in scenario 3 producers have access to new market channels (dairy market hub and processors), which reduce the sensitivity of producers' profit indicator to changes in milk price.

Table A.3.: Sensitivity analysis results of scenario 2 (use of artificial insemination to improve cattle breed)

Items	Milk production	Cumulative profit	Milk consumption	Improved cross breed (%total population)	milk traded to market hub (liter)	Milk traded to processors (liter)
Mean	100%	101%	99.9%	99.9%	NA	NA
Median	100%	100%	100.0%	100.0%	NA	NA
Standard Deviation	0.2%	26%	0.3%	0.4%	NA	NA
Minimum	99%	59%	99.3%	99.1%	NA	NA
Maximum	100%	146%	100.3%	100.4%	NA	NA

Table A.4.: Sensitivity analysis results of scenario 3 (artificial insemination and dairy market hub)

Items	Milk production	Cumulative profit	Milk consumption	Improved cross breed (%total population)	milk traded to market hub (liter)	Milk traded to processors (liter)
Mean	100%	101%	100.1%	100.0%	100%	100%
Median	100%	100%	100.0%	100.0%	100%	100%
Standard Deviation	1%	15%	0.9%	0.1%	3%	3%
Minimum	98%	76%	98.8%	99.8%	95%	95%
Maximum	103%	128%	101.7%	100.2%	107%	107%

Sensitivity analysis results showed that all performance indicators, except producers' cumulative profits, proved not to be sensitive (minor changes in output) to changes in milk prices. Although producers' cumulative profits are more sensitive to changes in milk price than to other performance indicators, even under the lowest milk price conditions, producers can still make positive profits in all tested scenarios (baseline and policy interventions). The lowest (minimum) level of producers cumulative profit were 56%, 59%, 76% for scenarios 1, 2, and 3 of cumulative profit values presented in table A.1., respectively. This indicates that producers can still make positive profit from dairy cattle activities even under lower milk prices than that imposed as an initial value. Similarly, policy interventions can still generate positive outcomes even at lower milk prices than initial milk price.

Appendix 4: Model equations

Cumulative profit per year(t) = Cumulative profit per year(t - dt) + (Profit per week - Adjusted annualy - Discounting) * dt
INIT Cumulative profit per year = 0
{USD}

INFLOWS:
Profit per week = Producers Profit Over Time
{USD/week}

OUTFLOWS:
Adjusted annually = PULSE(Cumulative profit per year,52,52)
{USD/week}

Discounting = Cumulative profit per year*Avg inflation rate
{USD/week}

Forage Mass(t) = Forage Mass(t - dt) + (Forage Growth Rate - Natural Depreciation Rate - Consumption Rate) * dt
INIT Forage Mass = 90*Land availability
{kg of feed}

INFLOWS:
Forage Growth Rate = (Actual Growth Rate*Land productivity per acre*Land availability)
{kg of feed/week}

OUTFLOWS:
Natural Depreciation Rate = Forage Mass/Decay Time
{kg of feed/week}

Consumption Rate = Total Cattle Population*Consumption Rate Per Cattle
{kg of feed/week}

Adult Male(t) = Adult Male(t - dt) + (Becoming Adult Male - Adult Male Death Rate - Adult Male Slaughter Rate) * dt
INIT Adult Male = 674
{cattle}

INFLOWS:
Becoming Adult Male = Preadult Male/Time to Mature
{cattle/week}

OUTFLOWS:
Adult Male Death Rate = Adult Male*Adults Fractional Death Rate
{cattle/week}

Adult Male Slaughter Rate = Adult Male*Adult Male Sale Rate
{cattle/week}

Calves(t) = Calves(t - dt) + (Calving - Calves Death Rate - Becoming Preadult Male - Becoming Preadult Female) * dt
INIT Calves = 1256
{cattle}

INFLOWS:
Calving = DELAY3((Breeding Rate*Survival rate), Gestation Period)
{cattle/week}

OUTFLOWS:
Calves Death Rate = Calves*Calves Fractional Death Rate
{cattle/week}

Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

Dry cows(t) = Dry cows(t - dt) + (Becoming Breeding Female + Drying - Breeding Stock Slaughter Rate - Breeding Stock Death Rate - Becoming Milk Producers) * dt
INIT Dry cows = 1002
{Cattle}

INFLOWS:
Becoming Breeding Female = Preadult Female/Time to Mature
{cattle/week}

Drying = Milk Producing Cows/Lactation period
{cattle/week}

OUTFLOWS:
Breeding Stock Slaughter Rate = Dry cows/Average Breeding Period
{cattle/week}

Breeding Stock Death Rate = Dry cows*Breeding Stock Fractional Death Rate
{cattle/week}

Becoming Milk Producers = Calving+Mixed breed dairy cattle.AI Calving
{cattle/week}

Gestation Delay(t) = Gestation Delay(t - dt) + (Breeding Rate - Calving - Still born rate) * dt
INIT Gestation Delay = 1140
{cattle}

INFLOWS:
Breeding Rate = (((Dry cows+Milk Producing Cows)*Number of offspring per birth*Number of births per cattle per year*Fertilization Success Rate*Actual effect of profit on production)/52)-Mixed breed dairy cattle.AI breeding rate
{cattle/week}

OUTFLOWS:
Calving = DELAY3((Breeding Rate*Survival rate), Gestation Period)
{cattle/week}

Stillborn rate = DELAY3((Breeding Rate*Fractional Abortion Rate), Gestation Period)
{cattle/week}

Dairy market hub center(t) = Dairy market hub center(t - dt) + (Milk Sales Rate to dairy market hub center – dairy market hub sales to processors - Individual buyers) * dt
INIT Milk collection centre = 0
{liter}

INFLOWS:
Milk Sales Rate to dairy market hub Center = Produced Milk*Fractional sales rate to dairy market hub centers
{liter/week}

OUTFLOWS:
Milk market hub sales to processors = Milk market hub center*Fractional sales rate to processors
{liter/week}

Individual buyers = Dairy market hub center*Dairy market hub center sales rate to individual consumers
{liter/week}

Milk Producing Cows(t) = Milk Producing Cows(t - dt) + (Becoming Milk Producers - Drying - Milk Producing Cows Death Rate) * dt
INIT Milk Producing Cows = 800
{cattle}

INFLOWS:
Becoming Milk Producers = Calving+Mixed breed dairy cattle.AI Calving
{cattle/week}

OUTFLOWS:
Drying = Milk Producing Cows/Lactation period
{cattle/week}

Milk Producing Cows Death Rate = Milk Producing Cows*Breeding Stock Fractional Death Rate
{cattle/week}

Milk Production Per Cow(t) = Milk Production Per Cow(t - dt) + (Change in Milk Production) * dt
INIT Milk Production Per Cow = 70
{liter/cattle}

INFLOWS:
Change in Milk Production = Local Cow Milk yield per cow per week-Milk Production Per Cow
{liter/cattle/week}

Preadult Male(t) = Preadult Male(t - dt) + (Becoming Preadult Male - preadult Male Sales Rate - Preadult Male Death Rate - Becoming Adult Male) * dt
INIT Preadult Male = 443
{cattle}

INFLOWS:
Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

OUTFLOWS:
preadult Male Sales Rate = Preadult Male*Preadult Male Fractional sales rate
{cattle/week}

Preadult Male Death Rate = Preadult Male*Preadult Male Fractional Death Rate
{cattle/week}

Becoming Adult Male = Preadult Male/Time to Mature
{cattle/week}

Preadult Female(t) = Preadult Female(t - dt) + (Becoming Preadult Female - Becoming Breeding Female - Preadult Female Death Rate - Preadult Female Sales Rate) * dt
INIT Preadult Female = 1028
{cattle}

INFLOWS:
Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

OUTFLOWS:
Becoming Breeding Female = Preadult Female/Time to Mature
{cattle/week}

Preadult Female Death Rate = Preadult Female*Preadult Female Fractional Death Rate
{cattle/week}

Preadult Female Sales Rate = Preadult Female*Preadult Female Fractional Sales Rate
{cattle/week}

Processors(t) = Processors(t - dt) + (CC sales to PROC - Consumers) * dt
INIT Processors = 0
{liter}

INFLOWS:
Dairy market hub center sales to processors = Dairy market hub center*Fractional sales rate to processors
{liter/week}

OUTFLOWS:
Selling to consumers = Processors/Processing time
{liter/week}

Produced Milk(t) = Produced Milk(t - dt) + (Milk Production - Producers Own Consumption Rate - Milk sales rate to individual consumers - Milk sales rate to traders - Milk Sales Rate to dairy market hub center - Surplus rate) * dt
INIT Produced Milk = Milk Producing Cows*Local Cow Milk yield per cow per week
{liter}

INFLOWS:
Milk Production = (Milk Producing Cows*Local Cow Milk yield per cow per week*Actual movement)+(Mixed breed dairy cattle.Milk Producing Cows*Improved Cow Yield per Week*Actual movement)
{liter/week}

OUTFLOWS:
Producers Own Consumption Rate = Produced Milk*Fractional milk consumption rate by producers
{liter/week}

Milk sales rate to individual consumers = Produced Milk*Fractional sales rate to individual consumers
{liter/week}

Milk sales rate to traders = Produced Milk*Fraction sales rate to traders
{liter/week}

Milk Sales Rate to dairy market hub Center = Produced Milk*Fractional sales rate to dairy market hub center
{liter/week}

Surplus rate = Unsold Surplus
{liter/week}

Producers Cumulative Profit(t) = Producers Cumulative Profit(t - dt) + (Producers Profit Over Time) * dt
INIT Producers Cumulative Profit = 0
{USD}

INFLOWS:
Producers Profit Over Time = ((Milk sales rate to individual consumers*Milk Price per Liter at Individual Consumers Market)+(Milk sales rate to traders*Milk Price per Liter at Traders Market)+(Milk Sales Rate to dairy market hub center*Milk Price per Liter at dairy market hub center))-Total Weekly Operational Cost
{USD/week}

Actual effect of profit on production = MIN((DELAY3(Effect of profit on production,52)),1)
{unitless}

Actual Growth Rate = Normal Growth Rate*Forage Density Effect On Forage Growth
{1/week}

Actual movement = SMTH3(Transhuman movement, 8)
{unitless}

Actual Rainfall = IF Policy Switch 1=0 then (Rainfall) Else (Drought Period*Rainfall)
{mm/week}

Adults Fractional Death Rate = (0.053/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Adult Male Sale Rate = 0.7/52
{1/week}

AI = 0
{unitless}

AI fractional success rate = 0.6
{unitless}

AI introduction time = If time <156 then 0 Else 1
{unitless}

Artificial Insemination Cost per Service = 18.3
{USD/AI}

Expected artificial insemination breeding rate = Proportion of AI use*AI fractional success rate*Expected natural breeding rate
{cattle/week}

Average Breeding Period = 416
{week}

Average Cost of Feed Concentrate per Household = 155.1/52
{USD/household/week}

Average Cost of Purchasing Fodder per Household = 277/52
{USD/household/week}

Average Cost of Using Crop Residues per Household = 16/52
{USD/household/week}

Average Cost of Using Other Farmers Bull per Service = 1.5
{USD/household/year}

Average Expenditure per Household on Animal Health = 326.8/52
{USD/household/week}

Average Fodder Planting Cost per Household = 1.7/52
{USD/household/week}

Avg inflation rate = 0.0544/52
{1/week}

Actual AI used = If Expected artificial insemination breeding rate = 0 then 0 ELSE Mixed breed dairy cattle.AI breeding rate/Expected artificial insemination breeding rate
{unitless}

Breeding Stock Fractional Death Rate = (0.053/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Calves Fractional Death Rate = (0.053/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Dairy market hub center sales rate to individual consumers = 0.2
{1/week}

Dry matter intake = Forage Mass per Cattle*Effect of cattle population movement on forage harvest efficiency
{kg of feed/cattle/week}

Contract farming = if time < 156 then 1 else Institution
{unitless}

Cost of Artificial Insemination Service Over Time = Number of Artificial Insemination Services per week*Artificial Insemination Cost per Service*Actual AI used
{USD/week}

Change in Cattle Population = Total Cattle Population/init(Total Cattle Population)
{unitless}

Decay Time = 104
{week}

Desired Artificial Insemination Attempt per Cow = 1
{AI/cattle}

Desired feed = INIT(Total feed provided per cattle)

{kg of feed/cattle/week}

Desired Percentage of Breeding Cows Serviced With AI = 0
{unitless}

Do nothing = 1
{unitless}

Do nothing 1 = 1
{unitless}

Drought Period = If time >104 and time <312 Then (0.65) Else (1)
{mm/week}

Feed volume per acre per year = 8000/52
{kg of feed/acre}

Effect of accessng supplementary feed on milk production = (Percentage of farmers accessing supplementary feed/0.57)^1
{unitless}

Effect of milk production increase due to policy on VC channels = SMTH1(Normalized milk production based on baseline results,5)
{unitless}

Effect of more produced milk on own consumption = Effect of milk production increase due to policy on VC channels^0.7
{unitless}

Effect of profit on production = MIN(((Smoothed producers profit/init(Smoothed producers profit))^0.5),1)
{unitless}

Effect of Changes in Milk Supply on Price = (Smoothed Milk Supply/init(Smoothed Milk Supply))^-0.0635
{unitless}

Expected natural breeding rate = ((Milk Producing Cows+Dry cows)*Number of births per cattle per year*Number of offspring per birth)/52
{cattle/week}

Extra Energy cost per mixed breed cattle = 0.067
{USD/cattle/week}

Fractional Abortion Rate = (0.02/52)*Resource Availability Effect on Cattle Mortality
{unitless}

Fractional milk consumption rate by producers = 0.62*Contract farming*Effect of more produced milk on own consumption
{1/week}

Fractional sales rate to dairy market hub center = (1-Fraction sales rate to traders-Fractional sales rate to individual consumers-Fractional milk consumption rate by producers)*Policy Switch 2
{1/week}

Fractional sales rate to individual consumers = 0.23*Contract farming*Effect of milk production increase due to policy on VC channels
{1/week}

Fractional sales rate to processors = 0.8
{1/week}

Fraction sales rate to traders = 0.15*Contract farming*Effect of milk production increase due to policy on VC channels
{1/week}

Gestation Period = 39
{week}

Hub introduction time = If time <156 then 0 Else 1
{unitless}

Improved Cow Yield per Week = Reference Milk Production for Improved Cattle*Effect of feed ratio on milk yield
{liter/cattle/week}

Institution = 1
{unitless}

Lactation period = 36
{week}

Lagged rainfall = DELAY(Rainfall 1, 12)
{mm/week}

Lagged Impact of Rainfall on Forage Growth Rate = SMTH1(Impact of Rainfall on Forage Growth,Lag Time,0.25)
{unitless}

Lag Time = 16
{week}

Land productivity per acre = (Lagged Impact of Rainfall on Forage Growth Rate*Dry matter volume per acre per year)
{kg of feed/acre}

Pasture land = 11152.7
{acre}

Local Cow Milk yield per cow per week = Reference milk production of Local Cattle*Effect of feed ratio on milk yield
{liter/cattle/week}

Male to Female Ratio = ((Adult Male/(Dry cows+Milk Producing Cows)),0.01)
{unitless}

Calve Male to Female Ratio = 0.5
{unitless}

Market hub = 0
{unitless}

Milk Price per Liter at Individual Consumers Market = 0.48* Effect of Changes in Milk Supply on Price*Price sensitivity
{USD/liter}

Milk Price per Liter at Traders Market = 0.4* Effect of Changes in Milk Supply on Price*Price sensitivity
{USD/liter}

Milk Price per Liter at Milk Collection Center = 0.4* Effect of Changes in Milk Supply on Price*Price sensitivity
{USD/liter}

Minimum Wage per Hour in Tanzania = 0.26
{USD/hr}

Normalized cattle population movement = Total Cattle Population/INIT(Total Cattle Population)
{unitless}

Normalized milk production based on baseline results = If Produced Milk<18130 Then (1) Else (Baseline milk production/Produced Milk)
{unitless}

Normal Growth Rate = 1
{1/week}

No Drought = 1
{unitless}

Number of Artificial Insemination Services per week = Number of Cattle Fertilized with Artificial Insemination*Desired Artificial Insemination Attempt per Cow
{AI/week}

Number of births per cattle per year = 0.67*Resource Availability Effect on Cattle Fertility
{calving/cattle/year}

Number of Cattle Fertilized with Artificial Insemination = Proportion of AI use*Expected natural breeding rate
{cattle/week}

Number of Households in Study Area = 106
{household}

Number of Households Using Animal Health Service = 104
{household}

Number of Households Planting Fodder = 2
{household}

Number of Households Purchasing Fodder = 3
{household}

Number of Households Using Crop Residues = 32
{household}

Number of Households Using Feed Concentrate = 7
{household}

Number of Labor Hours Spent per Household on Cattle per Week = 100.65
{hrs/household/week}

Number of offspring per birth = 1
{cattle/calving}

Percentage of farmers accessing supplementary feed = 0.57
{unitless}

Number of Households Using Other Farmers Bull = 99
{households}

Policy Setting = 1
{unitless}

Policy Setting 1 = 1
{unitless}

Policy Setting 2 = 1
{unitless}

Policy Switch1 = if(Do nothing=1)then(0)else(Policy Setting*AI)
{unitless}

Policy Switch 1 = if(No Drought=1)then(0)else(Policy Setting 1*Scenario 3)
{unitless}

Policy Switch 2 = (if(Do nothing 1=1)then(0)else(Policy Setting 2*Marketing hub))*Hub introduction time
{unitless}

Preadult Female Fractional Sales Rate = 0.01/52
{1/week}

Preadult Female Fractional Death Rate = (0.053/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Preadult Male Fractional Death Rate = (0.053/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Preadult Male Fractional sales rate = 0.9/52
{1/week}

Price sensitivity = 1
{unitless}

Processing time = 1
{week}

Proportion of AI use = Desired Percentage of Breeding Cows Serviced With AI*Policy Switch1*AI introduction time
{unitless}

Reference Milk Production of Improved Cattle = 51.2*Effect of accessing supplementary feed on milk production
{liter/cattle/week}

Reference milk production of Local Cattle = 13.82*Effect of accessing supplementary feed on milk production
{liter/cow/week}

Resource Availability Effect on Cattle Fertility = MIN(((Smoothed Dry Matter Intake per Cattle/INIT(Smoothed Dry Matter Intake per Cattle))^1),1)
{unitless}

Resource Availability Effect on Cattle Mortality = (Smoothed Dry Matter Intake per Cattle/INIT(Smoothed Dry Matter Intake per Cattle))^-1
{unitless}

Forage Mass per Cattle = Forage Mass/Total Cattle Population
{kg of feed/cattle}

Scenario 3 = 0
{unitless}

Smoothed milk supply = SMTH3(Produced Milk, 4, 9444)
{liter}

Smoothed producers profit = DELAY3(Producers Profit Over Time,52)
{USD/week}

Smoothed Dry Matter Intake per Cattle = SMTH3(Consumption Rate Per Cattle,52)
{kg of feed/cattle/week}

Survival rate = 1-Fractional Abortion Rate
{unitless}

Time to Mature = 130
{week}

Time to become Preadult = 52
{week}

Total Adult Cattle = Adult Male+Dry cows
{cattle}

Total Animal Health Service Cost = Number of Households Using Animal Health Service*Average Expenditure per Household on Animal Health
{USD/week}

Total Bull Service Cost = (Number of Households Using Other Farmers Bull*Average Cost of Using Other Farmers Bull per Service)/52
{USD/week}

Total Cattle Population = (Total Young Cattle+Total Adult Cattle+Milk Producing Cows+Mixed breed dairy cattle.Total Mixed Breed Cattle Population)*Actual movement
{cattle}

Total Cattle Population = (Total Young Cattle+ Total Adult Cattle+ Milk Producing Cows+ Mixed breed dairy cattle.Total Mixed Breed Cattle Population)
{cattle}

Total Cost of Using Crop Residues = Number of Households Using Crop Residues*Average Cost of Using Crop Residues per Household
{USD/week}

Total feed provided per cattle = Dry matter intake
{kg feed/cattle/week}

Total Feed Concentrate Cost = Number of Households Using Feed Concentrate*Average Cost of Feed Concentrate per Household
{USD/week}

Total Fodder Planting Cost = Number of Households Planting Fodder*Average Fodder Planting Cost per Household

{USD/week}

Total Labor Cost = Total Number of Hrs Spent on Livestock Activities*Minimum Wage per Hour in Tanzania*0
{USD/week} {This cost is been multiplied by zero to exclude from the model. The reason for this is that almost all of these labor hours are for household members due to transhumance activities – if we multiply these labor hours by minimum wage, then dairy production becomes unrealistically unprofitable. However, we kept it in the model for reference}

Total extra energy cost of mixed breed cattle = (Mixed breed dairy cattle.Total Mixed Breed Cattle Population*Extra energy cost of mixed breed cattle+(Mixed breed dairy cattle.Milk Producing Cows*Extra energy cost of mixed breed cattle))
{USD/week}

Total Number of Hrs Spent on Livestock Activities = Number of Households in Study Area*Number of Labor Hours Spent per Household on Cattle per Week
{hrs/week}

Total Purchased Fodder Cost = Number of Households Purchasing Fodder*Average Cost of Purchasing Fodder per Household
{USD/week}

Total Weekly Operational Costs = Cost of Artificial Insemination Service Over Time+Total extra energy cost of mixed breed cattle+(((Total Labor Cost+Total Animal Health Service Cost+Total Fodder Planting Cost+Total Cost of Using Crop Residues+Total Feed Concentrate Cost+Total Purchased Fodder Cost+Total Bull Service Cost)*Change in Cattle Population))
{USD/week}

Total Young Cattle = Calves+Preadult Male+Preadult Female
{cattle}

Transhuman movement = IF Lagged rainfall <12 then (0.77) Else (1)
{unitless}

Unsold Surplus = Produced Milk-Producers Own Consumption Rate-Milk sales rate to individual consumers-Milk sales rate to traders-Milk Sales Rate to Milk Collection Centers
{liter/week}

Kilosa.Mixed (cross) breed dairy cattle:

Adult Male(t) = Adult Male(t - dt) + (Becoming Adult Male - Adult Male Death Rate - Adult Male Slaughter Rate) * dt
INIT Adult Male = 0
{cattle}

INFLOWS:
Becoming Adult Male = Preadult Male/Time to Mature
{cattle/week}

OUTFLOWS:
Adult Male Death Rate = Adult Male*Adults Fractional Death Rate
{cattle/week}

Adult Male Slaughter Rate = Adult Male*Adult Male Sale Rate
{cattle/week}

Calves(t) = Calves(t - dt) + (Mixed Breed Calving + AI Calving - Calves Death Rate - Becoming Preadult Male - Becoming Preadult Female) * dt
INIT Calves = 0
{cattle}

INFLOWS:
Mixed Breed Calving = DELAY3((Mixed breed cattle breeding rate*Survival rate), Gestation Period)
{cattle/week}

AI Calving = DELAY3((AI breeding rate*Survival rate), Gestation Period)
{cattle/week}
OUTFLOWS:
Calves Death Rate = Calves*Calves Fractional Death Rate
{cattle/week}

Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

Dry cows(t) = Dry cows(t - dt) + (Becoming Breeding Female + Drying - Breeding Stock Slaughter Rate - Breeding Stock Death Rate - Becoming Milk Producers) * dt
INIT Dry cows = 0
{Cattle}

INFLOWS:
Becoming Breeding Female = Preadult Female/Time to Mature
{cattle/week}

Drying = Milk Producing Cows/Lactation period
{cattle/week}

OUTFLOWS:
Breeding Stock Slaughter Rate = Dry cows/Average Breeding Period
{cattle/week}

Breeding Stock Death Rate = Dry cows*Breeding Stock Fractional Death Rate
{cattle/week}

Becoming Milk Producers = Mixed Breed Calving

{cattle/week}

Gestation Delay(t) = Gestation Delay(t - dt) + (Mixed breed cattle breeding rate + AI breeding rate - Mixed Breed Calving - Still born rate - AI Calving) * dt
INIT Gestation Delay = 0
{cattle}

INFLOWS:
Mixed breed cattle breeding rate = ((Dry cows+Milk Producing Cows) *No of offspring per calving*Productive portion of breeding stock*Fertilization Success Rate)/52
{cattle/week}

AI breeding rate = Kilosa.Expected artificial insemination breeding rate*Kilosa.Actual effect of profit on production
{cattle/week}

OUTFLOWS:
Mixed Breed Calving = DELAY3((Mixed breed cattle breeding rate*Survival rate), Gestation Period)
{cattle/week}

Still born rate = DELAY3(((Mixed breed cattle breeding rate+AI breeding rate)*Fractional Abortion Rate), Gestation Period)
{cattle/week}

AI Calving = DELAY3((AI breeding rate*Survival rate), Gestation Period)
{cattle/week}

Milk Producing Cows(t) = Milk Producing Cows(t - dt) + (Becoming Milk Producers - Drying - Milk Producing Cows Death Rate) * dt
INIT Milk Producing Cows = 0
{cattle}

INFLOWS:
Becoming Milk Producers = Mixed Breed Calving
{cattle/week}

OUTFLOWS:
Drying = Milk Producing Cows/Lactation period
{cattle/week}

Milk Producing Cows Death Rate = Milk Producing Cows*Breeding Stock Fractional Death Rate
{cattle/week}

Preadult Male(t) = Preadult Male(t - dt) + (Becoming Preadult Male - preadult Male Sales Rate - Preadult Male Death Rate - Becoming Adult Male) * dt
INIT Preadult Male = 0
{cattle}

INFLOWS:
Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

OUTFLOWS:
preadult Male Sales Rate = Preadult Male*Preadult Male Fractional sales rate
{cattle/week}

Preadult Male Death Rate = Preadult Male*Preadult Male Fractional Death Rate
{cattle/week}

Becoming Adult Male = Preadult Male/Time to Mature
{cattle/week}

Preadult Female(t) = Preadult Female(t - dt) + (Becoming Preadult Female - Becoming Breeding Female - Preadult Female Death Rate - Preadult Female Sales Rate) * dt
INIT Preadult Female = 0
{cattle}

INFLOWS:
Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio
{cattle/week}

OUTFLOWS:
Becoming Breeding Female = Preadult Female/Time to Mature
{cattle/week}

Preadult Female Death Rate = Preadult Female*Preadult Female Fractional Death Rate
{cattle/week}

Preadult Female Sales Rate = Preadult Female*Preadult Female Fractional Sales Rate
{cattle/week}

Adults Fractional Death Rate = (0.04/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Adult Male Sale Rate = 0.7/52
{1/week}

Average Breeding Period = 416
{week}

Breeding Stock Fractional Death Rate = (0.04/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Calves Fractional Death Rate = (0.04/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Fractional Abortion Rate = (0.02/52)*Resource Availability Effect on Cattle Mortality

{unitless}

Gestation Period = 39
{week}

Lactation period = 44
{week}

Male to Female Ratio = ((Adult Male/Dry cows+ Milk Producing Cows),0.01)
{unitless}

Male to Female Ratio = 0.5
{unitless}

No of offspring per calving = 1
{cattle/calving}

Preadult Female Fractional Sales Rate = 0.01/52
{1/week}

Preadult Female Fractional Death Rate = (0.04/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Preadult Male Fractional Death Rate = (0.04/52)*Resource Availability Effect on Cattle Mortality
{1/week}

Preadult Male Fractional sales rate = 0.9/52
{1/week}

Number of births per cattle per year = 0.73*Resource Availability Effect on Cattle Fertility
{calving/cattle/year}

Resource Availability Effect on Cattle Fertility = MIN(((Kilosa.Smoothed Dry Matter Intake per Cattle/INIT(Kilosa.Smoothed Dry Matter Intake per Cattle))^1),1)
{unitless}

Resource Availability Effect on Cattle Mortality = (Kilosa.Smoothed Dry Matter Intake per Cattle/INIT(Kilosa.Smoothed Dry Matter Intake per Cattle))^-1
{unitless}

Survival rate = 1-Fractional Abortion Rate
{unitless}

Time to Mature = 130
{week}

Time to become Preadult = 52
{week}

Total Mixed Breed Cattle Population = Calves+Preadult Male+Adult Male+Dry cows+Preadult Female+Milk Producing Cows
{cattle}

Figure A.1: Effect of cattle population on forage harvest efficiency

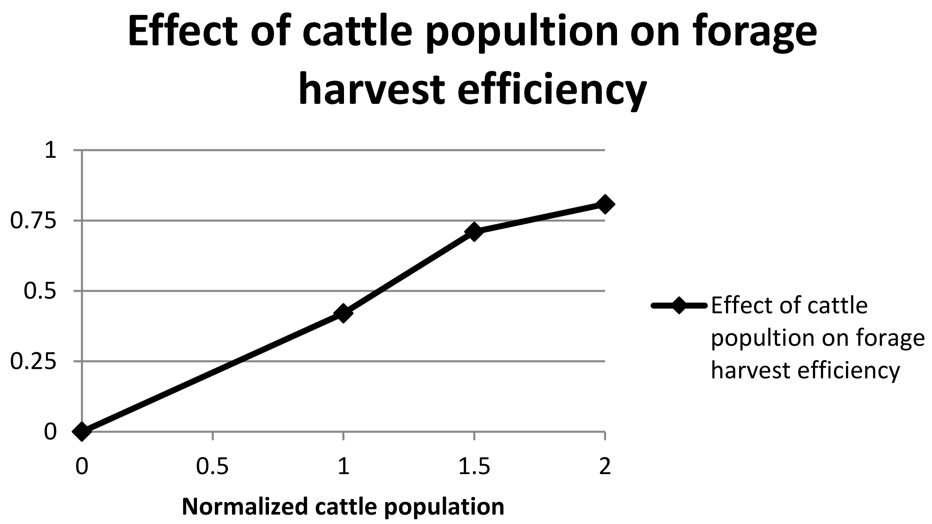

Figure A.2: Effect of feed ratio on milk yield

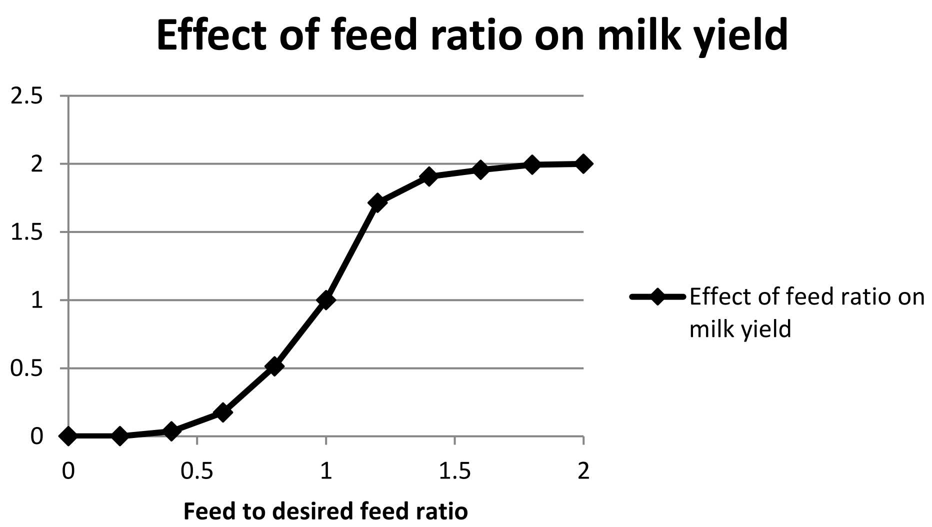

Figure A.3: Fertilization success rate

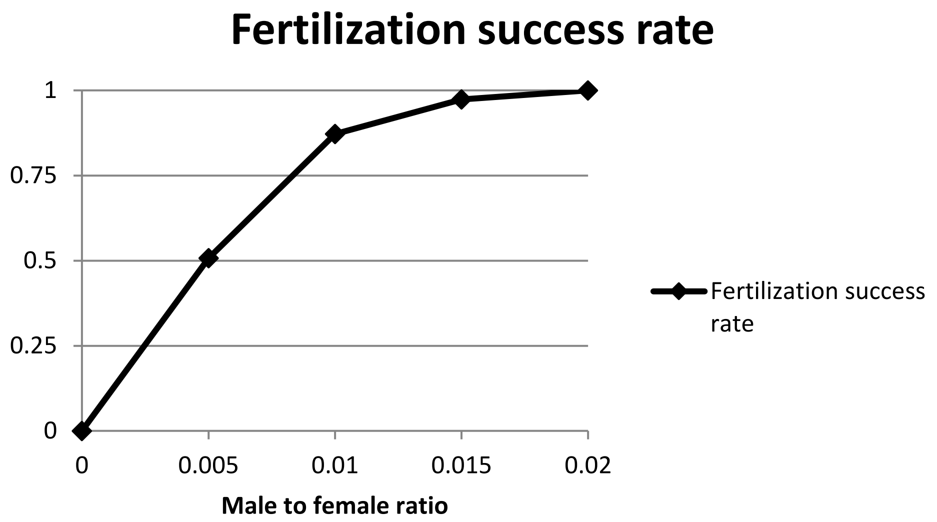

Figure A.4: Forage density effect on forage growth

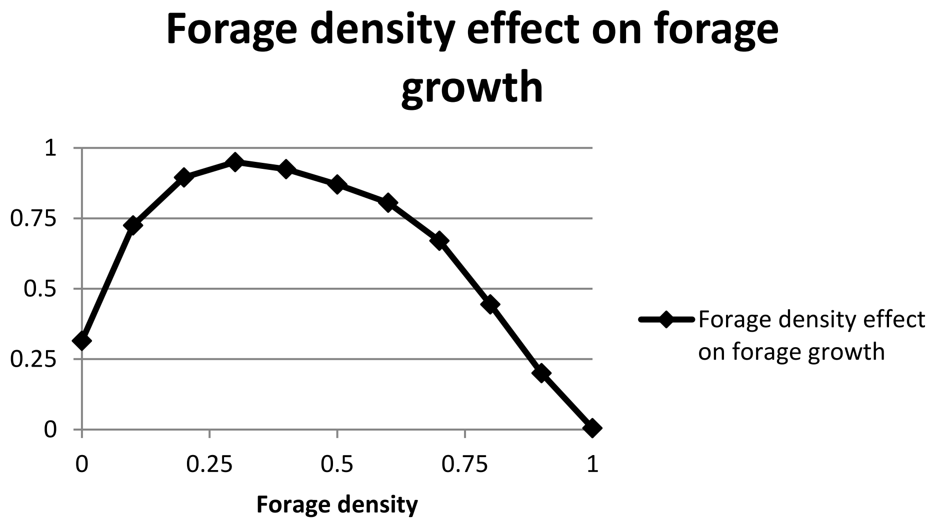

Figure A.5: Impact of rainfall on forage growth

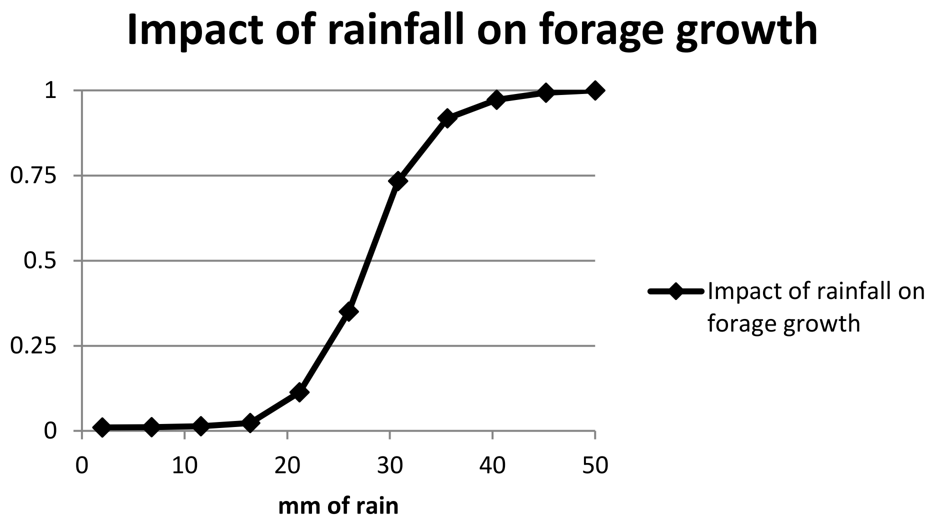

Figure A.6: Average rainfall pattern in study area