Supplemental Materials

Study area

Annual rainfall averages range from 60 inches of rainfall in the eastern portion of the state to 10 inches in the western portion of the state and is categorised by ten different climate divisions. Climate variations across the diverse ecoregions of Texas consist of many warm-season and cool-season native and non-native forage species and systems; grasses, legumes, forbs, shrubs (Barnes et al., 2003, 2007). The dominant warm- and cool-season grasses used for cattle grazing pasture and hay production are bermudagrass (*Cynodon dactylon*) and annual ryegrass (*Lolium multiflorum*), respectively (TAMU-AE, 2019). Likewise, a wide range of crops is grown throughout Texas such as corn (*Zea mays*), sorghum (*Sorghum bicolour*), wheat (*Triticum aestivum*), and cotton (*Gossypium hirsutum*) having the most planted acres throughout the state (TAMU-AE, 2019).

Texas cattle population submodel

First, the TXWFB model calculates the initial mature cows for each region starting at the selected calving month, where historical beef cow population data values were used as initial model values (USDA-NASS, 2019). Typically, the Texas calving season is synchronised with periods when abundant high-quality forage is available to meet nutrient demands during lactation (Herring 2014). The TXWFB model simulates one calving season per year, though, in reality, some operations may elect to have two calving seasons; fall and spring (Tedeschi and Fox, 2018). After cows have calved, the first delay is in the suckling duration and represents the number of months (5-8) that a calf consumes milk from a cow. This period ends with the calf being weaned and results in the cessation of milk production. The mature cows that have not been lost to death or culled by the “per cent cow weaning” variable are rebred at a selected time (e.g., 1-3 months after calving). The mature cow herd then goes through another delay period of being in a bred cow herd (bred cow duration) and bred back cows are delayed until the last trimester of pregnancy is finished; 9 months. Under optimal conditions, each mature cow will produce a new calf annually (285-365-day cycle), and cows that fail to re-breed or progress in pregnancy may be culled. Cull cows are determined by subtracting the designated percent (e.g., 0 to 1) of successful calving, weaning, breeding, and pregnancy stages from one and represents the proportion of cows moved into the cull cow stock.

As the mature cow herd enters the calving stock, the calf stock is simultaneously filled, and calves are delayed by the same suckling duration time until weaning occurs and then calves progress to the weaned calf stock or experience mortality (Figure 1C). Weaned calves are then delayed until they reach one year of age to leave the cow-calf phase and become yearlings, which are then sold or retained. Sold calves enter a new stock and then exit the model boundaries, meaning these calves are no longer accounted for in the model. However, retained yearlings are separated as stocker cattle or replacement heifers, which is determined by a stocker to heifer development ratio (Figure 2C). Retained cattle that are designated as stocker cattle and remain in the stocker phase for a select duration and are then sent to the feedlot stage. At this point, the model aggregates each subscripted region's stocker cattle into the High Plains region as most Texas cattle feedlots are located in this region. The end of the feedlot stage is a model boundary, and those cattle are assumed to have experienced mortality by natural causes or slaughter for meat production.

Conversely, retained heifers enter a series of stocks and are delayed representing breeding at puberty (13-15 months) and pregnancy. Ideal management aims for heifers to produce their first calf at 24 months of age, becoming mature cows, and then joining the mature cow breeding herd.

The bull population dynamics reflect a chosen ratio of bulls required for a given quantity of mature cows (e.g., one bull for 25 mature cows).

Cattle growth submodel

The daily rate of growth was calculated using the shrunk weight gain equation (**SWG**; Tedeschi and Fox, 2018; see Equation 1 in Table 1A). Consequently, as cattle growth rates and weight change in each cattle stage, the amount of dry matter intake (**DMI**) is altered and impacts total nutrient intake (Mcal/d).

Cattle nutrition submodel

The calf nutrition model equation differs slightly from the other cattle stages as adjusted milk and forage DMI relationships are accounted for based on peak milk level (**PML**) and digestible energy (**DE**) levels of forage (Tedeschi and Fox, 2009; Equations 3-6 in Table 1A). The PML affects calf forage intake and forage intake of calves (**DMI_F**; Equation 7 in Table 1A). The DMI of forage (**DMI_F**) was adjusted for temperature effects using the current effective temperature index (**$CETI_{TF}$**; Equation 8 in Table 1A) and using the metabolisable energy of forage (**ME_F**; Equation 9 in Table 1A) value, calf forage metabolisable energy intake (**MEI_F**; Equation 10 in Table 1A). Once the DE and PML of milk, MEI_F and DMI were calculated they were aggregated to determine total daily ME consumed by the calf (**ME_C**), net energy for growth (**NEg** Equation 12 in Table 1A), net energy for maintenance (**NEm**), net energy maintenance requirement (**NEmr**), feed for maintenance (**FFM**), and feed for growth (**FFG**; Equations 11-16 in Table 1A). The FFG was used as an input to the shrunk body weight (**SBW**) gain equation and therefore provides feedback to calf daily growth rate and total body weight (**BW**), which moves into the weaned calf weight stock at weaning (Figures 3C and 4C).

Once calves are weaned, the inclusion of milk nutritional dynamics to DMI was excluded from all other TXWFB model cattle nutrition formulations. Instead, NEm intake and DMI equations developed and recommended by the National Academies of Science, Engineering, and Medicine (NASEM, 2016) were used, including the NEm intake of heifers, weaned calves, stockers and feeder cattle (Calves NEm intake; Yearlings NEm intake; Equations 17 and 18 in Table 1A). The estimated NEm intake value was then used for DMI estimation (Equation 19 in Table 1A).

Similar to the suckling calf DMI, the DMI for heifers, calves, stockers, and feeder cattle were adjusted using $CETI_{TF}$ and seasonal total digestible nutrients (**TDN**; discussed in the Forage and evapotranspiration section) of forage and feedstuffs, for each cattle type, was used as input for Equations 8-19. The diets for heifers, weaned calves, and stocker calves assume a fixed supplement that allows pasture and hay diets to meet NEmr. However, the feedlot diet is less simplistic in terms of the unique TDN values that contribute to MEc and does not assume a supplementation, as feedlot diets are not limited by pasture or hay quality unless designated by the user. The model allows the user to use a premade feedlot ration or create a new feedlot ration. The creation of new rations requires TDN and dry matter (**DM**) values as inputs, which can be obtained from the Ruminant Nutrition System (**RNS**) feed library for ruminant livestock (Tedeschi and Fox, 2018).

Alternatively, the equation used for the estimation of cow and bull DMI were determined by a more simplistic approach, static, that utilises a predetermined per cent mature body weight ranging from 1 to 3% throughout a year (Equations 20 and 21 in Table 1A). Therefore, this model parameter can be set to reflect changes in cow and bull nutrient demands throughout the year (e.g., breeding, late gestation, and nursing). Similar to the supplementation of other cattle types, the bull and cows also are assumed to receive supplementation to maintain NEmr. Water, the most limiting nutrient, is captured for each cattle type using three published water intake equations from the RNS (Tedeschi and Fox, 2018) and the NASEM (2016) recommended equations by Arias and Mader (2011) for heifers, calves, stockers, and feedlot animals (Equations 22-24 in Table 1A; Figure 5C).

Forage and evapotranspiration submodel

Annual evapotranspiration growth curve coefficient (**ETkc**) values are parameterised as lookup functions that can be adjusted for each region and cattle type to provide robust management scenarios. The Penman-Monteith equation was used to calculate daily evapotranspiration (**ET**) for each region and can be altered for both tall and short grass types (Zotarelli et al., 2010). The user can adjust the daily rate of forage growth to simulate different levels of forage production. Regional, historic, climate data was integrated into Vensim to produce forage ET values and includes: Temperature (˚C), wind speed (m/s), solar radiation W/m^2, pressure (Pa), relative humidity (%), snow water equivalent (SWE; kg/m^2), precipitation (mm), and day length (s; DAYMET, 2019; NOAA, 2019a). The TDN values for forage are determined by a seasonal lookup function that reflects the variation in forage quality within each region (Figure 6C).

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Table 1A. Primary model equations (**EQ**) for cattle population, growth, nutrition, forage and evapotranspiration, water footprint, supply chain, and water scarcity submodels (NASEM, 2016; Tedeschi and Fox, 2009, 2018).

EQ#	Equation
1	$SWG = 13.91 \times RE^{0.9116} \times SBW^{-0.6837}$
2	$NEgr = \left(DMI - \frac{NEmr}{NEma}\right) \times NEga$
3	$DMI_M = BW^{a} \times e^{(b + c \times BW)}$
	$a = -0.3895 + 0.4477 \times PML - 0.0197 \times PML^2$
	$b = 0.3224 - 1.3594 \times PML + 0.0588 \times PML^2$
	$c = -0.00244 - 0.00337 \times PML + 0.00018 \times PML^2$
4	$DMI_{MTF} = DMI_M \times CETI_{TF}$
5	$MEI_M = DMI_{MTF} \times DE_M$
6	$\mathrm{DE}_F = 4.409 \times TDN_F$
7	$DMI_F = \frac{1}{DE_F^2} \left\{ BW^{(-0.3895-0.0197\times PML^2)}\, e^{[BW-(-0.00244-0.00337XPML)-1.3594\times PML]} \times \left[BW^{0.4477\times PML}[-32.5704+(27.9016-7.66732\times DE_F)\times DE_F] \times e^{[(0.0588+0.00018\times BW)PML^2]} + BW^{(1.3895+0.0197\times PML^2)} \times e^{[BW(0.00244+0.00337\times PML)+1.3594\times PML]} \left(0.4738 + DE_F\left[-0.4059 + DE_F(0.11154 - 0.003273\times PML) + 0.01191\times PML\right] - 0.0139046\times PML\right) + BW^{(0.3895+0.0197\times PML^2)} e^{[BW(0.00244+0.00337\times PML)+1.3594\times PML]} \times \left(-10.3049 + DE_F\left[8.82778 + DE_F(-2.42586+0.362681\times PML) - 1.31981\times PML\right] + 1.54065\times PML\right)\right]\right\}$

Table 1A. Continued.

EQ#	Equation
8	$\text{DMI}_{FTF} = \text{DMI}_{F} \times \text{CETI}_{TF}$
9	$\text{ME}_{F} = 0.9611 \times \text{DE} - 0.2999$
10	$MEI_{F} = DMI_{F} \times ME_{F}$
11	$MEc = \dfrac{MEI_{M} + MEI_{F}}{\text{DMI}_{MTF} + \text{DMI}_{FTF}}$
12	$\text{NEg} = 1.1376 * \text{MEc} - 0.1198 * \text{MEc}^{2} + 0.0076 * \text{MEc}^{3} - 1.2979$
13	$NEm = 1.1104 * \text{MEc} - 0.0946 * \text{MEc}^{2} + 0.0065 * \text{MEc}^{3} - 0.7783$
14	$\text{NEmr} = 0.077 * \text{SWB}^{0.75}$
15	$\text{FFM} = \text{NEmr}/\text{NEm}$
16	$\text{FFG} = \left((\text{DMI}_{\text{MTF}} + \text{DMI}_{\text{FTF}}) - \text{FFM}\right) \times \text{Neg}$
17	$Calves: NEm\ intake$ $= BW^{0.75} \times (0.2435 \times NEm - 0.0466 \times NEm^{2} - 0.1128)$
18	$Yearlings: NEm\ intake$ $= BW^{0.75} \times (0.2435\ X\ NEm - 0.0466 \times NEm^{2} - 0.0869$
19	$DMI = \dfrac{total\ NEm\ intake}{NEm\ concetration}$
20	$Cow\ DMI = BW \times cow\ percent\ BW$
21	$Bull\ DMI = BW \times bull\ percent\ BW$

TABLE 1A. Continued.

EQ#	Equation	
22	$WI = \begin{cases} 7.3 + 0.0805 \times FBW - 0.00008 \times FWB^2 - 1.225 \times CETI + 0.002327 \times FBW \times CETI + 0.041 \times CETI^2 \\ 6.3 + 0.106 \times FBW - 0.000096 \times FBW^2 - 1.6 \times CETI + 0.00226 \times FBW \times CETI + 0.056 \times CETI^2 \end{cases}$	Growing heifers, steers, or bulls Finishing cattle
23	$DWI = 5.92 + 1.03\,DMI\;0.04\,SR + 0.45\,Tmin$	
24	$DWI = -7.31 + 1.00\,DMI + SR + 0.30\,THI$	

[1]Where RE is retained energy (Mcal/d) and SBW is body weight [BW (kg) × 0.96]; RE is substituted with NEgr which is net energy required for growth (Mcal/d).
[2]Where DMI is dry matter intake (kg/d), NEmr is net energy required for maintenance (Mcal/d), NEma is net energy available for maintenance (Mcal/d), and NEga is net energy available for growth (Mcal/kg).
[3]Where DMI_M is milk DMI (kg/d); PML is peak milk level (kg/d); and a, b, and c are parameters used in the DMI_M equation.
[4]Where DMI_{MTF} is the DMI of milk adjusted for temperature (kg/d) and $CETI_{TF}$ is the current effective temperature index factor for temperature.
[5]Where MEI_M is the metabolisable energy intake (Mcal/d), DMI_M is the milk dry matter intake (kg/d), and DE_M is the milk digestible energy.
[6]Where DE_F is digestible energy of forage (Mcal/d), and TDN_F is the total digestible nutrients of forage (kg/d).
[7]Where BW is body weight (kg), DE_F is forage DE (Mcal/kg), DMI_F is forage dry matter intake (kg/d), *e* is exponential, and PML is peak milk level (kg/d).
[8]Where DMI_{FTF} is the DMI of forage adjusted for temperature (kg/d), DMI_F is the DMI of forage (kg/d), and $CETI_{TF}$ is the current effective temperature index factor for temperature (dimensionless).
[9]Where ME_F is the metabolisable energy of forage (Mcal/kg), and DE_F is the forage digestible energy from equation 6.
[10]Where DMI_F is the DMI of forage (kg/d) and ME_F is the metabolisable energy of forage (Mcal/kg; equation 9).
[11]Where, MEc is the total ME consumed per d (Mcal/kg), and MEI_M is the metabolisable energy intake of milk (Mcal/d), MEI_F is the metabolisable energy of forage (Mcal/d), DMI_{MTF} is the daily milk DMI adjusted for temperature (kg/d), and DMI_{FTF} is the daily forage DMI adjusted for temperature (kg/d).
[12]Where NEg is net energy for growth (Mcal/kg) and MEc is metabolisable energy consumed (Mcal/kg).
[13]Where NEm is net energy for maintenance (Mcal/kg) and MEc is metabolisable energy consumed (Mcal/kg).
[14]Where NEmr is net energy required for maintenance (Mcal/d) and SWB is the shrunk body weight (kg).
[15]Where FFM is feed for maintenance (kg/d), NEmr is net energy required for maintenance (Mcal/d), and NEm is net energy for maintenance (Mcal/kg).
[16]Where, FFG is feed for growth (kg/d), DMI_{MTF} is DMI of milk adjusted for temperature (kg/d) and DMI_{FTF} is DMI of forage adjusted for temperature (kg/d), and FFM is feed for maintenance (kg/d), and NEg is net energy for growth (Mcal/kg).
[17-18]Where NEm intake is the dietary net energy maintenance concentration (Mcal/kg of DM) and BW is the average body weight (kg/d).
[19]Where, DMI = dry matter intake (kg/d), total NEm intake is the total net energy maintenance intake (Mcal/d), and NEm concentration is net energy maintenance concentration (Mcal/kg of DM).
[20-21]Where, Cow DMI and Bull DMI is the dry matter intake of a mature cow or bull (kg/d); BW is the constant mature body weight of a cow or bull; per cent, BW is the user-determined per cent body weight [dimensionless(1 to 3%)] required by a cow and a bull throughout a production year (i.e., 365 days) using table function.
[22]Where, WI is water intake (L/d); FBW is full (unshrunk) body weight (kg); CETI is the current effective temperature index (˚C).

[23-24] Where DWI is daily water intake (L/d); DMI is dry matter intake (kg/d); SR is solar radiation (W/m^2); Tmin is the daily minimum ambient temperature (˚C); and THI is the temperature-humidity index (dimensionless).
[25]Where SWD is the specific water demand (m^3/t), ET is evapotranspiration (m^3/ha), and Feedstuff is the total production of a particular feedstuff per unit of area (t/ha).
[26]Where PFU is the Functional Unit of the Product desired reporting unit for the beef water footprint in live weight (LW; kg), carcass weight (CW; kg) or boneless beef per animal (kg), cattle weight is the live weight of the cattle (kg), and X is the factor of adjustment LW to calculate FUP for LW = 1, CW = per cent, boneless = per cent.
[27]Where WF_B is the beef water footprint (L water/kg meat), CWU_{TP} is the total accumulated cattle water use (L/d) of each cattle type during a single production cycle to produce a finished feedlot animal (L) and product is the total amount of meat (kg LW, CW, boneless) product from a single feedlot animal (kg).
[28]Where RCWU is regional cattle water use (m^3/d), RCTWU is cattle type (bulls, cows, heifers, calves, suckling calves, stocker cattle, and feedlot cattle) water use (m^3/cattle/d) in each region, and RCP_T is the regional cattle population of each cattle type (cattle/d).
[29]Where ALRFW is the freshwater for Texas livestock (m^3/d), AFW is the total available freshwater (m^3/d), and LWC is the livestock water coefficient (%/d).
[30]Where RCWC is the regional cattle water consumption ratio (Dimensionless/d).
[31]Where TCWU is the total Texas cattle water use (m^3/d).

Supplemental materials figure legend

Fig. 1C. Simplified calf population dynamics of calves on milk, weaned and sold. Rectangles represent stocks (accumulations) which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). The graph displays an example of the numerical accumulations and production delays of calves, weaned calves, and calves to be sold stocks.

Fig. 2C. Stock and flow diagram of the stocker, feedlot and replacement heifers population dynamics (above). Rectangles represent stocks (accumulations), all of which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). Multiple heifer stocks kept annual heifer crops separate until joining the mature cow herd. The graph displays the aggregation of stocker cattle from the ten regions to the feedlot phase in region one (High Plains).

Fig. 3C. Description of the cattle designated for meat production and replacement heifers daily weight gain stock and flow diagram (above). Rectangles represent stocks (accumulations), all of which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). The graph displays an example of calf (i.e., suckling calf), weaned calf, stocker, and feedlot cattle progression for each production cycle. Overlap exists because new calves enter the production chain before the current animals obtaining mature weight and leaving the chain (i.e., slaughter).

Fig. 4C. Example of the dry matter intake (DMI) structure that is dynamically connected to the weight stock and flow structure for each cattle type (i.e., calf, weaned calf, stocker, feedlot, and replacement heifers; above). Rectangles represent stocks (accumulations), all of which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). The graph shows the behaviour of specific growth and nutrition factors for three feedlot periods.

Fig. 5C. Example of drinking and servicing water estimation structure (above). Rectangles represent stocks (accumulations), all of which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). The graph displays the daily drinking and servicing water levels of a single animal in during each feedlot phase duration for subsequent years in region one.

Fig. 6C. Example of the daily forage growth, hay, and specific water demand (SWD; m^3/ton) stock and flow structure (above). Rectangles represent stocks (accumulations), all of which use fixed delays that hold cattle for an explicit duration (e.g., suckling and breeding durations) where outflows are only active at the end of that duration via rates (arrow-cloud-hourglass). The graph displays the daily values for total forage production and SWD for each season and the associated hay SWD of hay that has been stored from the previous year.