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An integrative bio-physical approach to determine the greenhouse gas emissions and carbon sinks of a cow and her offspring in a beef cattle operation: A system dynamics approach

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HIGHLIGHTS

- We estimate the carbon footprint of a cow over her entire life cycle inclusive of that of her 8 offspring over a 154-month period.
- We developed a system dynamics model to model the carbon footprint over her life-cycle inclusive of her physiological stages.
- We model six scenarios regarding the global warming potential of CH4 and the sequestration rates of the manure-based carbon.
- The cumulative net emissions vary between 19tCO2e (a net source) and -12.6tCO2e (a net sink) per ton of meat produced.

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ABSTRACT

Context: Regenerating the planet through natural resource protection, restoration and prudent land management must currently be one of the most important policy and operational objectives at all scales from local to international level. The beef cattle production sector has both an important role and a responsibility to this end as well.
Objective: We estimated the greenhouse gas emissions of a cow over her entire life inclusive of that of her offspring taking cognisance of her physiological stages under different scenarios relative to the meat produced (carcass weight) to determine the range of emissions and/or sinks that are possible from a grassland beef cattle farming operation in South Africa.
Methods: We constructed a system dynamics model populated by the energy and carbon flows of a hypothetical cow and her 8 offspring over their entire life cycle of 154 months. The birth of the cow and her offspring represents a marginal addition to an otherwise stable global herd. The cow and her calves thus constitute an additional carbon pool birthed and nurtured by the mature cow. By making provision for the physiological stages of the cow and her calves and allowing for typical variations in the metabolisable energy during these stages, we estimated the cumulative net greenhouse gas emissions relative to the cumulative amount of meat (carcass weight) produced. Using a purpose-built system dynamics model, we modelled several scenarios providing a range of outcomes depending on the parameter values.
Results and conclusions: On the one end of the spectrum, we applied a global warming potential (GWP_{100}) of methane of 28 and that 10% of the carbon contained in the manure is sequestered in the soil. Under this scenario the cumulative net emissions are estimated as 19.1 tCO_2e per ton meat. Thus, the sources of emissions exceed the sinks. At the other end of the spectrum the figure turns into a net sink of approximately 12.6 tCO_2e if a global warming potential (GWP*) of 8 is used and if 70% of the carbon in the manure is sequestered in the soil, a figure attainable in healthy soils with active microbial life and sufficient grass cover and good land management. Under these conditions the net addition of the cow and her calves to an otherwise stable global herd lead to the reduction in greenhouse gas emissions. All these figures exclude additional carbon sequestration through accelerated grass regrowth and increased litter deposits and could thus be deemed conservative.

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Significance: Discussions with respect to the reduction of greenhouse gas emissions from livestock must consider the full life cycle of the female animal and her offspring, inclusive of the virtual (or embedded) carbon, the appropriate estimate of the global warming potential of methane acknowledging that it is a short-lived climate pollutant, as well as the condition of the rangelands. Much more effort should therefore be directed towards improving the soil and land use management, including incentive measures and knowledge sharing, as it has a mutually reinforcing impact on the mitigation of greenhouse gas emissions and the sequestration of carbon.

1. Introduction

1.1. Prelude

Regenerating the planet through natural resource protection, restoration and prudent land management must currently be one of the most important policy and operational objectives at all scales from a local to an international level. This includes both a concerted effort to reduce greenhouse gas (GHG) emissions and the maximisation of carbon sequestration. Being the largest land user globally, agriculture has an important role to play within this quest, most notably also with respect to livestock production – grass-fed beef being the topic of this paper.

1.2. Pathways to reduce greenhouse gasses in agriculture

The official carbon dioxide equivalent (CO_2e) emissions of livestock in South Africa comprises a small portion of the total emission load, namely 5.5%, with beef cattle contributing approximately 4.5% of total CO_2e emissions (RSA, 2020). This percentage is the same order of magnitude as the USA (3.9%; EPA, 2018). While low, it can and should still be reduced to avoid further negative perceptions and to make its own rightful contribution to mitigating the effects of climate change (Hayek et al., 2021), reducing its environmental impact (Poore and Nemecek, 2018), and reducing nitrogen pollution (Uwizeye et al., 2020). This reduction can happen through several pathways, some of them being mutually inclusive.

1.3. Carbon sequestration

The first pathway entails an increase in carbon sequestration from the production of crops and improved rangeland management, which has much potential in reducing emissions (Lal, 2010; WFO, 2012; Retallack, 2013; Meissner et al., 2017; Franzluebbers, 2020). Lal (2010), for example, estimated that the potential of soil organic carbon sequestration by world cropland soils through the adoption of good management practices (i.e. climate-smart conservation and regenerative agriculture practices) is 0.4 to 1.2 billion ton carbon annually, and if soils and vegetation are considered together, the equivalent could be a decrease of approximately 50 ppm of atmospheric CO_2 by 2100 to 2150. Expressed differently, this implies that nearly 89% of agricultural carbon mitigation potential can be achieved by soil carbon sequestration through improved rangeland management, improved cropland management, restoration of soils and degraded lands, bio-energy, water management, and eco-friendly agricultural waste management (Lal, 2010; Retallack, 2013; Qambrani et al., 2017). Thus, climate-smart conservation and regenerative agriculture (CA/RA) which include livestock should become a priority. See Section 2 for an elaboration on this topic.

1.4. Accounting for methane's global warming potential

The second pathway pertains to updating the way in which methane (CH_4) is accounted for in terms of i) the enteric CH_4 estimates, and ii) the global warming potential (GWP) of CH_4. With respect to enteric CH_4, from results of calorimetry trials on a wide range of forages and forages plus supplements in Australia, Charmley et al. (2016) regressed CH_4 production on gross energy intake (GEI). These Australian forages correspond to forages and forages plus supplements used in South Africa. The prediction equation has a R^2 of 0.93 and the estimate of CH_4 production was 6.3% of GEI. This resulted in a mean relationship of metabolisable energy (ME) equal to 0.905 digestible energy (DE) instead of the generally accepted relationship of ME = 0.82 DE (Hales, 2019).

With respect to the GWP of CH_4, the conventional calculation (GWP_{100}) is obtained by expressing the warming potential of CH_4 relative to CO_2 estimates, and that ranges between 28 and 34 times the warming potential of CO_2 (EPA, 2018). This has recently been contested due to the half-life of CH_4 in the atmosphere (only 8.6 years) after which it decreases rapidly (Muller and Muller, 2017), as well as its relatively short lifespan of 10–17 years in the atmosphere (Prather et al., 2012; Muller and Muller, 2017; Allen et al., 2018; Lynch et al., 2020). This is brief compared to the 1000+ years lifespan of CO_2 (Archer and Brovkin, 2008; Joos et al., 2013; Buis, 2019; Lynch et al., 2021). The principle behind the approach (referred to as GWP*) is that the impact of short-lived atmospheric pollutants (SLCP) (in this instance CH_4) cannot be equated linearly to the long-lived CO_2 as no single number will equate the impact on global warming of these gasses satisfactorily. This is since their rate of decay differs so vastly, as is also explored in Ridoutt (2021a, 2021b), Costa Jr. et al. (2021) and Dillon et al. (2021).

Based on Smith et al. (2021a), which updated the estimates of Lynch et al. (2020), the warming potential of CH_4 can be calculated as follows:

$$E^*_t = 128 \times E_{CH4(t)} - 120 \times E_{CH4(t-20)}$$

if a cut-off point of 20 years is considered where E_{CH4} is CH_4 emissions for time *t* and time *t-20*, using AR5 GWP values as reported in Myhre et al. (2013). The warming potential of CH_4 is thus dynamic and varies pending the emission loads in *t* and *t-20.* In the case study herein we assumed the marginal addition of one cow and her offspring which acts as an additional carbon pool with the balance of the global herd being constant and that implies a warming potential of CH_4 of 8 within the 20-year period. This is the difference between the factors in the equation above, 128 and 120. We also compared the outcome of the results of using a GWP* of 8 against that of a GWP of 28.

1.5. Inclusive accounting

The third pathway is to apply a comprehensive method of accounting for GHG emissions. This is to include the contribution of the animals to be a carbon sink and not just a source of emissions. Currently, carbon accounting focuses almost exclusively on the enteric and manure-based CH_4 emissions as a source of emissions. The fact that livestock production also contributes to the sequestration of carbon is not accounted for. It is assumed that, in addition to the enteric emissions, the carbon intake by the animal in the form of feedstock is oxidised and returned to the atmosphere. We wish to contest this argument based on the metabolic processes in the animals, notably among grass-fed cattle, as well as the depositing of carbon into the soil from the manure. More so since the distinction between grass-fed cattle and cattle that are not grass-fed, is important from a carbon emissions vantage point (Lynch, 2019). This potentially has far-reaching consequences in terms of how to optimise land use and herd management towards an accelerated and improved rangeland carbon sequestration and is elaborated on in Section 2.

1.6. Metabolism enhancement and nitrogen reduction

There are various other pathways, not pursued further herein but mentioned for the sake of completeness, including the reduction of GHG emissions through enhanced animal metabolism and the reduction in nitrogen requirements. Enhanced animal metabolism can result because of i) improved genomic selection (Pryce and Haile-Mariam, 2020), ii) diet manipulation and the use of dietary supplements (Eckard and Clark, 2018; Kinley et al., 2020; Al-Azzawi et al., 2021), and/or iii) rumen modification (Broucek, 2018). The reduction of nitrogen (N) applications by means of chemical fertilisation is also an important priority, both from an atmospheric and soil pollution point of view (Prather et al., 2015; Martínez-Dalman et al., 2021).

1.7. Research focus

As noted above, on-farm carbon footprint is a function of both emissions and sequestration – determining these is not simple because of the variables affecting both carbon fluxes. In brief, growing plants use CO_2 from the atmosphere and nutrients, such as N, from the soil and redistribute it among different pools, including both above and below ground living biomass, dead residues and soil organic matter (SOM). The CO_2 and other GHG, such as CH_4 and nitrous oxide (N_2O), are released into the atmosphere by plant respiration, the decomposition of dead plant biomass and SOM, and by combustion. Thus, there is a continuous flux in and out of the pools (Dillon et al., 2021).

An important omission in on-farm carbon footprint assessments is the carbon cycles within the animal to enable the physiological functions of maintenance, pregnancy, lactation and growth (i.e. the product which is to be marketed). The within-animal pool completes the carbon cycle and, therefore, needs to be considered as well (Holder, 2020; Mitloehner, 2020). This within-animal carbon pool should be considered as a virtual carbon sink (Atkinson et al., 2011; Chen et al., 2020) when measuring the carbon footprint of animal husbandry in relation to the product (meat) produced. This can provide an expression both in relation to the carbon footprint and in production efficiency benchmarks of farmers. The large number of variables involved in estimating the carbon footprint is an integrated function of external fluxes and internal pools which requires modelling. To do this we employed a system dynamics approach, the objective being to estimate the GHG outcomes of a beef cow throughout her lifecycle inclusive of 8 offspring. Before embarking on this one fundamental on-farm element within the carbon cycle, we turn to the treatment of the topic of carbon contained in the manure.

2. Terrestrial carbon sequestration from manure

Terrestrial ecosystems are an important global carbon sink, and the size thereof is related to the rangelands and other biomes of the world. Soil carbon sequestration (SCS) will, however, depend on a variety of factors such as existing soil carbon, soil type, climate and management practices (Smith et al., 2007). Although many rangelands have been badly degraded, it is possible to manage these efficiently and sustainably, thereby reversing degradation and net carbon loss into significant net carbon sequestration (Franzluebbers, 2010; Lal, 2010; Conant et al., 2017; Shrestha et al., 2020). Results of restoration ranged from 0.45 to 0.84 MgC/ha/y (Franzluebbers, 2010) and 0.105 to >1 MgC/ha/y (Conant et al., 2017).

Grazing herbivores like cattle, if managed prudently, also play a vital role by increasing forage diversity, efficient grazing, forage nutrient concentration, above-ground plant production, and the decomposition of plant material and the release of nutrients (Sacks et al., 2014; Shrestha et al., 2020). Nutrients gained from grazing return to the soil in the form of urine and manure, which accelerate the cycling of nutrients otherwise locked in above-ground vegetation biomass. Nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are bound to carbon in organic residues and only become available through decoupling and mineralisation by microbes. Carbon returns to the soil mostly through manure, whereas N returns to the soil mainly through urine. This implies that by increasing grazing intensity, decoupling will increase, and more C and N will return to the soil. Whereas some inorganic N can be found in manure pads, the majority of N is in organic forms and must be mineralised before it can be assimilated by plants or soil microbes (Evans, 2016).

Manure pad decomposition can be mediated by a variety of invertebrate organisms, including earthworms, flies, termites, ants and dung beetles. Dung beetles are among the most significant invertebrate contributors to manure decomposition in rangelands, with benefits to pasture growth, soil carbon and soil health (Doube, 2008). Their abundance, diversity and influence on nutrient cycling (Yoshihara and Sato, 2015) and carbon sequestration (Slade et al., 2016) are affected by factors associated with land use and management practices such as habitat quality, livestock insecticides (Floate, 1998), intensity of livestock production and grazing practices (Anderson et al., 1984; Evans, 2016). A major factor is soil health and biodiversity as this has a direct influence on soil carbon sequestration and thereby the success of the contribution thereto by dung beetles and other invertebrates. Acknowledging these constraints, they nevertheless have the potential to decompose 70–80% of manure pads (Anderson et al., 1984) within 80 days (Floate, 1998), primarily by burrowing and decomposing inside the soil. Depending on species diversity, they also accelerate N and C transfer from the grass-produced manure to the soil (Doube, 2008; Yoshihara and Sato, 2015). At the ecosystem level, dung beetles reduced GHG emissions by up to 7% and 12% respectively, mainly through large reductions in CH_4 emissions (Slade et al., 2016).

In the context of grazing management, appropriate practices will make more organic matter (food) available for soil organisms and thereby increasing their soil carbon sequestration work rate. Lopez-Collado et al. (2017), for example, found a high effectiveness (66.6%) of dung beetles where manure patches occur, but at the grassland (landscape) level the effectiveness was only 0.17% because manure pads cover a small fraction of the productive area. This implies that the greater the occurrence of manure in the landscape and the higher the grazing intensity (Frank et al., 2017), the better the effectiveness per unit area of dung beetles and other organisms in the soil food web to recycle carbon and other nutrients in the manure to the soil. Richardson and Richardson (2000) found that dung beetles bury a ton of wet manure per acre per day (~2 metric tons/ha) and remove 90% of the manure on the soil surface when using adaptive or planned multi-paddock (AMP) rotational grazing systems, management-intensive grazing system, or ultra-high-density grazing (UHDG). This pattern of grazing movement and density of herbivores (cattle) provide an easily located, relatively concentrated supply of manure. In practical terms this means that this type of grazing system will usually lead to greater increases in carbon content and sequestration of atmospheric carbon into soils than the light continuous grazing systems (Manley et al., 1997; Akala and Lal, 2000; Teague et al., 2011; Wang et al., 2015; Shrestha et al., 2020). For example, Akala and Lal (2000) found that the carbon sequestration under UHDG was 1 to 2.4 tC/ha/yr, almost 3 times higher than normal. Shrestha et al. (2020) showed that CH_4 uptake was 1.5 times greater in soils from AMP-grazed than non-AMP-grazed grasslands. If AMP is implemented in croplands with cover crops, the annual change in soil

Table 1
Soil carbon sequestration rates of cattle manure under different rangeland scenarios.

Ecosystem health class	Description of ecosystem health class in rangeland scenarios	Most plausible ranges of carbon sequestered in the soil from cattle manure	% used in the model	Sources
1 – Poor	Degraded ecosystem; large % bare soil and/or low plant cover and biodiversity; continuous grazing practices	5–20%	10%	Richardson and Richardson (2000)
2 – Moderate	Moderately degraded ecosystem; some bare soil patches and/or moderate plant cover and biodiversity; long rotation grazing practices typically with large camps	21–50%	40%	Akala and Lal (2000)
3 – Good	Healthy ecosystem; no bare soil with excellent plant cover and biodiversity; short rotation (planned) grazing practices with long or sufficient rest periods such as high or ultra-high density grazing systems	51–80%	70%	

carbon was shown to be 0.32 MgC/ha/year within the first 50 years with saturation being achieved after 155 years. At that time, a total soil organic carbon (SOC) stock increase of 16.7 MgC/ha could be reached (Poeplau and Don, 2015).

A World Bank report based on 30 studies (World Bank, 2012) estimated the soil carbon sequestration rates of African soils due to manure as being 224–427 kgC/ha/y, a range which agrees with our calculations in this study of 295.7 kgC/ha/y. However, based on the arguments on soil condition and grazing management above, we base our manure carbon sequestration estimates on three scenarios as indicated in Table 1.

3. Materials and methods

3.1. Introduction to system dynamics

System dynamics is a technical tool and a method used to describe and model a dynamically (i.e. ever-changing) and complex (i.e. multi-varied) system (Pruyt, 2013). Because of both its versatility and capability to model complex systems, system dynamics has been applied to a range of disciplines. These include environmental economics (Nkambule and Blignaut, 2017; Bester et al., 2019; Bester et al., 2020; Crookes et al., 2020), climate change (Sarindizaj and Zarghami, 2019; Arroyo and Miguel, 2020; Yuan et al., 2020), cropping or conservation agriculture (Smith, 2006) and livestock production (Godde et al., 2019; McKay et al., 2019). It is, therefore, a well-accepted and broadly endorsed means of investigation with broad application.

3.2. The model

The model comprises five sub-models (see Annexures 1–5) namely a feedstock sub-model, an animal production sub-model, an energy flow sub-model, an excrement sub-model and a GHG flow sub-model.

Sub-model 1 determines the feedstock requirement. This is driven by the gross energy (GE) requirement (MJ/month) for each of the physiological stages of the cow, namely growth (until adulthood), then maintenance, pregnancy and lactation. A maize-based supplement is provided for two months per year, and the consumption of grass makes up for the balance of the requirement, likewise for her offspring. This material flow in terms of energy, converted to biomass, is divided in terms of that which becomes excreted and the digestible portion of the feedstock.

Sub-model 2 models the life of the cow and her offspring. The cow's weight is determined by her birth weight, the weight accumulation and the date of her slaughter. The cow is born at the start of month 1, and she is slaughtered at the end of month 143 when her 8th calf is weaned. Her target weight is 525 kg, her first calf is born at the start of month 31, and she produces a calf every 15 months. While the cow has the biological ability to have a calf every 12 months, we acknowledge that in a herd context the calving percentage is between 65% and 85% and therefore have accommodated this by lengthening the period between calves to 15 months. This reduces the cow's theoretic potential of 10 calves to 8. The weaner weight, herein referring to the combined pre- and post-weaning weight, is determined by the birth weight, the monthly gain pre-weaning, and the monthly gain post-weaning. The calves are weaned after 8 months weighing 230 kg and are slaughtered after 18 months weighing 400 kg. The enteric and manure-based GHG emissions are calculated based on weight making provision for different emission factors at different stages (calf, heifer, adult cow and weaner).

The feedstock consumed and the excrement are allocated to the various metabolic components in sub-model 3 based on the energy hierarchy (Knox, 1979):

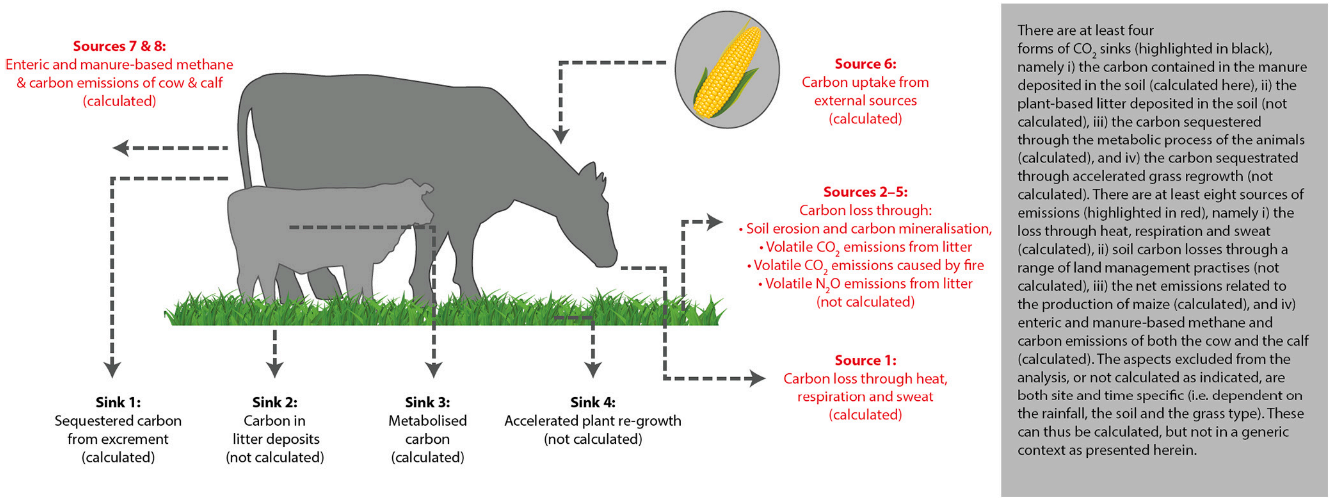
- Gross energy (GE) less the energy contained in the manure = digestible energy (DE).
- DE less the energy lost in fermentation and urine = metabolisable energy (ME).
- ME is allocated between net energy (NE) or energy retention, and heat loss (mainly respiratory) for each of the four physiological stages (growth, maintenance, lactation and pregnancy).

While it is possible to model the entire flow of energy through the system on an energy (MJ) basis, it is only possible to do so in terms of carbon up to the ME stage. The assimilation of ME carbon is based on the metabolisability of the diet which influences the efficiency of use of ME for the various physiological processes mentioned above (Pluske and Schlink, 2005). The efficiency of ME use (k) is calculated as the ratio of NE output to ME intake and varies depending on the process for which the ME is being used and the nature of the ME supply (McDonald et al., 2011). The GE intake required to meet NE requirements can be estimated by considering the digestibility of the diet for both the cow and her calf separately.

As indicated above, the energy contained in the excrement, notably also the urine, must be determined to estimate the ME. Sub-model 4 thus focuses on the estimation of the urine and excrement produced.

Sub-model 5 brings together the different sources and sinks of GHG emissions. The sources are i) the net GHG emissions emanating from the production of maize after subtracting the CO_2 sequestration by the maize plant from the emissions caused by producing the maize, ii) the enteric and manure-based GHGs (after making provision for their global warming potential) generated by the cow, and iii) her offspring, and iv) the CO_2 released by the cow and v) her offspring through heat loss, inclusive of respiratory losses.

The sinks include the portion of the carbon (after correcting for the oxidisation factor) contained in the manure that is deposited in the soil as well as the portion of the carbon (post correcting for oxidisation) that



There are at least four forms of CO_2 sinks (highlighted in black), namely i) the carbon contained in the manure deposited in the soil (calculated here), ii) the plant-based litter deposited in the soil (not calculated), iii) the carbon sequestered through the metabolic process of the animals (calculated), and iv) the carbon sequestrated through accelerated grass regrowth (not calculated). There are at least eight sources of emissions (highlighted in red), namely i) the loss through heat, respiration and sweat (calculated), ii) soil carbon losses through a range of land management practises (not calculated), iii) the net emissions related to the production of maize (calculated), and iv) enteric and manure-based methane and carbon emissions of both the cow and the calf (calculated). The aspects excluded from the analysis, or not calculated as indicated, are both site and time specific (i.e. dependent on the rainfall, the soil and the grass type). These can thus be calculated, but not in a generic context as presented herein.

Fig. 1. Greenhouse gas flows related to beef cattle production.

has been absorbed as net energy by all the animals during growth, pregnancy, lactation and maintenance. The net emissions (sinks less sources) are divided by the total meat (in slaughter weight) produced by both the cow at the end of her life, and her offspring. This generates a variable called tGHG/tmeat – slaughter or carcass weight (t = ton), with tGHG referring to tCO_2e; tCO_2e is used as the common unit. This variable is used to evaluate various scenarios (see also Fig. 1.)

3.3. Data and assumptions

The assumptions and external model inputs in support of the scenario as discussed above and the model design are provided in Table 2. The inputs are provided per sub-model with the respective sources and/or notes.

4. Results

4.1. Material and energy flows

As discussed above, we modelled the life of a cow born in month 1 weighing 35 kg with a mature weight of 525 kg, and which is slaughtered at the end of month 143, after weaning her 8th calf. Over her lifespan she gives birth to 8 calves which are slaughtered when they reach 400 kg in month 18. This implies that for most of her life she will have two live offspring, a calf and a weaner, acting as additional carbon pools.

Based on the various physiological stages of the cow, her GE demand and thus intake vary (Table 2). The digestive portions of the feedstock and the metabolic efficiencies also differ. Thus, the GE, DE and ME will vary as indicated in Fig. 2a. Gross energy peaks during lactation at 7125 MJ/month with DE varying between approximately 3050 and 4150 MJ/month and ME between 2500 and 3600 MJ/month (or between 82 and 118 MJ/day). The combined GE intake of the live offspring (Fig. 2b) peaks at about 6200 MJ/month, with DE varying between 1400 and 3400 MJ/month and ME between 1500 and 2850 MJ/month. This illustrates the broad range of the energy requirement for both the cow and her offspring depending on the physiological stage they are in as well as the ME demand. This is reflected in Tables 3a and 3b.

The gross energy intake (GEI) is the energy contained in the manure, fermentation, urine and ME, broken down in their physiological components, for the five sample months shown for both the cow and her offspring. The sample months are month 32, a month during which the cow receives a maize-based supplement; month 40, a month when the weaner is supported with a maize-based supplement; month 49, the month at which the first offspring is slaughtered; month 143, the month in which the cow is slaughtered; and month 154, the month in which the final weaner is slaughtered.

As indicated in Table 3b, the manure energy for the cow is for the most part 45%, thus a diet digestibility of 55%. When she, however, receives a supplement to augment her diet, the digestibility improves to 58% with the energy contained in the manure declining to 42%. The same pattern can be observed for the offspring with the digestibility improving during those months that a supplement is provided. As a result of the different feedstocks, and thus differences in the digestibility and consequent fluctuations in the energy associated with fermentation, ME as a fraction of GE varies between 48% and 51% for the cow and 45% and 50% for her offspring. This translates to a modelled ME as a fraction of DE that varies between 86.6% and 87.3% for the cow and 82.1% and 85.1% for her offspring. By far the largest portion of the ME for the cow is lost during pregnancy. The largest retained portion of NE for the cow (in the sample months) is for maintenance.

A major part of the animals' diet consists of carbon. It is thus possible to provide a carbon balance which mirrors the energy flows based on the principle of material throughput and that, as energy cannot be created or destroyed (first law of thermodynamics), the carbon contained in the food is never created nor destroyed; it only occurs in different formats at different stages. Tables 4a and 4b thus mimic Tables 3a and 3b, but from a carbon balance standpoint by calculating the carbon content embedded within each stage. The gross carbon intake for the cow is marginally less (171.6 kg/month compared to 174.3 kg/month) when supported by the maize-based supplement due to the higher energy content thereof (for the same MJ GE intake). The carbon in the manure is hence also reduced (64 kg compared to about 70 kg/month), but the digestible carbon is increased (107 kg compared to 104 kg/month) because of the increased digestibility of the supplement. As a result, the digestible carbon, when the cow is supported with the supplement, is 62% of the gross carbon intake compared to 60% for the other (non-supported) periods. The same can be observed for her offspring. The carbon contained in the form of net energy varies between 32% and 37% of gross carbon intake for the cow and 26% and 28% for the offspring.

The GEI is thus either lost by being excreted in the form of manure, fermentation, urine or heat, or it contributes to carbon build-up through the metabolic process in the form of net energy in the cow and her offspring. While the urine contains virtually no carbon, there is much

Table 2
Assumptions and external model inputs*

Variable	Unit	Value	Source/notes
Sub-model 1			
Number of days in month	day/Month	30.5	
Gross energy (GE) – Cow need per day	MJ/ton/day	Dry: 346.4 Lactating: 444.9 Growth: 400.41	These values are based on i. a ME requirement of 90.52 MJ/day, or 0.17 MJ/kg/day for a cow weighing 525 kg (Meissner et al., 1983) ii. ME = 0.905DE (based on Charmley et al., 2016) iii. rangeland digestibility of 55% (Meissner and Paulsmeier, 1995) Expressed in terms of MJ/ton/day
Cow daily maize-based supplement intake %	%/day of body weight	0.3%	Mare et al. (2020)
Cow maize-based supplement pulse train	Dimensionless	Month 31 and 32 to be repeated every 15 months	Assumption
Maize production GHG factor	tCO_2/ton	0.381	Blignaut et al. (2019)
Maize sequestration GHG factor	tCO_2/ton	0.52	Lal (2010) Smith et al. (2021b)
Weaner supplement pulse train	Dimensionless	Month 9 & 10 of calf's life	Assumption
Weaner daily supplement intake %	%/day of body weight	0.3%	Mare et al. (2020)
Gross energy (GE) – Weaner need per day	MJ/ton/day	400	Meissner et al. (1983)
Manure % – Maize-based supplement	%	22%	Supplement digestibility 78% based on the in situ DMD of maize varying from 87 to 91% (Brendon et al., 1987)
Gross calorific value – Maize-based supplement	MJ/ton	20,000	Based on the composition of a typical production supplement for beef cattle
Manure % – Grass	%	45%	Meissner and Paulsmeier (1995) (diet digestibility 55%)
Gross calorific value – Grass	MJ/ton	18,400	Charmley et al. (2016) Kaasik (2010)
Gross calorific value – Maize	MJ/ton	18,600	Kaasik (2010)
Carbon in manure % – Grass	tC/t manure	40	Assmann et al. (2015) Holter and Scholtz (2007)
Carbon in manure % – Maize-based supplement	tC/t manure	40	Assmann et al. (2015) Holter and Scholtz (2007)
Sub-model 2			
Cow life pulse train	Dimensionless	Cow is born at the start of month 1, and lives until month 143	Assumption
Cow target weight	Ton	0.525	Meissner et al. (1983)
Months before first calf	Month	30	Van der Westhuizen et al. (2001)
Calf birth weight	Ton	0.035	Bonsmara (2019)
Number of cows	Dimensionless	1	Assumption
Cow before calf pulse	Dimensionless	First calf is born start month 31	Bonsmara (2019)
Heifer CH_4 factor	tCH_4/ton	0.01733	Du Toit et al. (2013)
Cow CH_4 factor	tCH_4/ton	0.01625	Du Toit et al. (2013)
Cow slaughter pulse	Dimensionless	Cow slaughtered at the end of month 143 after weaning the 8th calf	Assumption
Weaning period	Month	8	NDA (2000)
Weaner weaning weight	Ton	0.23	Assumption based on Theron and Scholtz (1994)
Weaner time for target weight	Month	10	Assumption
Weaner target weight	Ton	0.4	Assumption
Weaner pulse train	Dimensionless	From month 39 (calf 8 months), for 10 months – repeated every 15 months	Assumption
LSU unit weight	Ton/LSU	0.45	Meissner et al. (1983)
Calf birth pulse	Month	First birth in month 31, and every 15 thereafter	Assumption based on Bonsmara (2019)
Weaner slaughter pulse train	Month	Slaughter calf on month 49 when first calf is 18 months – repeat every 15 months	Assumption based on ADG reported by Groenewald (2017)
Carcass as % of live weight	%	60%	Esterhuizen et al. (2008)
Calf CH_4 factor	tCH_4/ton	0.02264	Du Toit et al. (2013)
Weaner grass CH_4 factor	tCH_4/ton	0.01981	Du Toit et al. (2013)
Weaner supplement CH_4 factor	tCH_4/ton	0.01487	Du Toit et al. (2013)
GHG CH_4 (100) factor	tCO_2/tCH_4	28 and 8	EPA (2018) Smith et al. (2021b)
Sub-module 3			
Urine energy factor	MJ/tUrine	0.00870854*1e+006	Ieropoulos et al. (2012)
MJ/CH_4 factor	MJ/tCH_4	50,000	World Nuclear Association (2018)
Net energy – Cow growth	% ME	72%	
Net energy – Cow maintenance	% ME	62%	
Net energy – Cow lactation	% ME	53%	
Net energy – Cow pregnancy	% ME	13.3%	Kaasik (2010)
Sub-model 4			
N in Urine	tN/tUrine	0.015	Bristow et al. (1992)
Cow urine/day	tUrine/day	0.016	Based on Reece (2004)
Weaner urine/day	tUrine/day	0.006	Based on Reece (2004)

(continued on next page)

Table 2 (*continued*)

Variable	Unit	Value	Source/notes
Urine water content	%	98%	Bristow et al. (1992)
Excretion C:N ratio	tC/tN	18	Teixeira et al. (2019) Assmann et al. (2015) Holter and Scholtz (2007)
		Sub-model 5	
Manure-based carbon to soil	%	10 to 70% (Table 1)	Scenarios

[*] All coloured variables in Annexures 1–5 refer to assumptions and external inputs and are highlighted here.

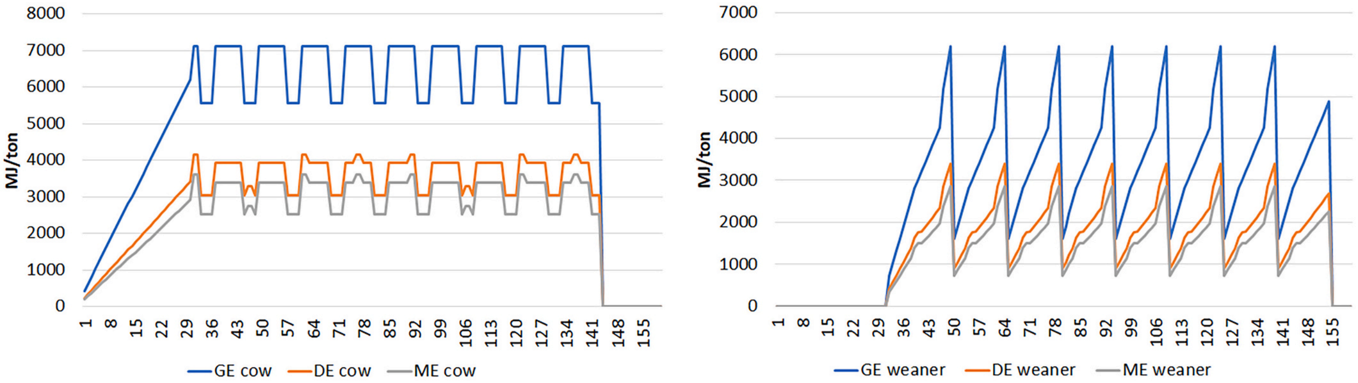


Fig. 2. a) Distribution of the cow's GE, DE and ME over the cow's lifetime; b) The distribution of the calves GE, DE and ME over their lifetimes.
Note: GE = gross energy, DE = digestible energy, ME = metabolisable energy.

carbon lost during fermentation ($C/CH_4 = 12/16$) and through heat loss, including respiration. The carbon contained in the manure plus that which is contained in the net energy, however, does constitute the bulk of the carbon balance. When these two components are combined, it varies between 72% and 76% of gross carbon intake for the cow and 66% and 67% for her offspring. The impact thereof deserves further analysis and is the subject of the next section.

4.2. *Greenhouse gas flows*

Through sub-model 5, the combined impact of the cumulative net impact of both the sources of emissions and the carbon sinks are calculated and expressed in terms of meat produced over the entire life cycle of the cow and her offspring bearing in mind that they represent a net marginal addition of beef cattle to an otherwise stable global herd. The sources of the emissions include the net CO_2 emissions of the maize-based supplement, the enteric and manure-based emissions of the cow and her offspring, as well as the CO_2 loss through respiration and heat. The sinks include the carbon contained in the manure that is sequestered in the soil and that which is contained through the metabolic process of the animals.

Fig. 3 shows the cumulative net amount of GHG produced in ton (sources less sinks), divided by the cumulative carcass weight of the animals over time for two scenarios. The first scenario uses a GWP_{100} of CH_4 equal to 28 (EPA, 2018) and that 10% of the carbon contained in the manure is sequestered in the soil (see Table 1) through natural biological processes. The second scenario uses a GWP* of CH_4 equal to 8 (Lynch et al., 2020; Smith et al., 2021a) and if 70% of the carbon contained in the manure is sequestrated in the soil. It is shown that in the first scenario the sources exceed the sinks and that at the end of the life cycle the value converges towards a net source of emissions of approximately 19.1 tCO_2e/t meat produced up until month 154. In the second scenario, the sinks outstrip the sources depicting a net sink of 12.6 tCO_2e/t meat produced. This outcome is achieved in conditions with healthy soils and active microbial life and sufficient grass cover and good land management. It should be noted that during the initial years the value is shown as zero since no meat has been produced and the denominator is zero. The cumulative net emissions until month 49 is divided by the meat produced in month 49, thus resulting in the big initial deviation from zero.

The values reported in Fig. 3 are disaggregated for month 154 in Table 5 and Fig. 4. This is done by dividing the total sources of the emissions (heat loss, fermentation, urine, etc.) of both the cow and the weaner from birth to date of slaughter, and the sinks of carbon contained in net energy as well as the carbon sequestered contained in the manure, by the total carcass weight. The net impact is derived by subtracting the sources from the combined value of the carbon contained in the net energy and the manure. It should be noted that the total carbon sink per ton of meat in the net energy component remains constant under both scenarios. This is since it is not affected by the change in either the global warming potential of CH_4 or the amount of the carbon contained in the manure sequestered.

In addition to the two scenarios depicted in Figs. 3 and 4, the results from four intermittent scenarios are indicated in Table 6 by varying the amount of the carbon that is sequestrated in the soil and the GWP of CH_4.

5. Discussion

The value reported in Table 6 using a GWP of CH_4 of 28 times that of CO_2 of approximately 19 kg CO_2e/kg meat produced compares favourably with that reported by Opio et al. (2013) for Eastern European countries. They indicated a range varying from 14 kg CO_2e/kg meat produced for Eastern European countries to 76 kg CO_2e/kg meat produced for South Asian countries using the GLEAM model. This is also within the 2–19.6 kg/kg product range as estimated by Desjardins et al. (2014) for Canada, the United States, the European Union, Australia and Brazil. Furthermore, the value reported herein is also not too dissimilar from that by Clark and Tilman (2017) who reported a range from 28 kg CO_2e/kg beef to 60 kg CO_2e/kg beef employing a life cycle approach. To illustrate the importance of including carbon sequestration, Schroeder et al. (2012) showed the reduction in emissions from 33.8 kg CO_2e/100 kg bone-free meat to 29.4 kg CO_2e/100 kg bone-free meat for production systems in the UK and from 45.7 kg CO_2e/100 kg bone-free meat to 25.4 kg CO_2e/100 kg bone-free meat for beef production systems in Brazil once sequestration is considered.

Table 3a
Distribution of the gross energy intake of the cow and her calves at five different sample months.

		Month	GE intake	Manure energy	DE	Ferment. Energy	Urinary energy	ME	Heat loss				NE			
									Growth	Maint.	Preg.	Lact.	Growth	Maint.	Preg.	Lact.
								MJ/month								
Cow	Cow supported with supplement	32	7125	2983	4142	427	99	3616	0	614	0	541	0	1578	0	883
	Weaner supported with supplement	40	7125	3206	3918	427	99	3393	0	790	496	0	0	2031	76	0
	1st calf slaughtered end month	49	7125	3206	3918	427	99	3393	0	647	0	411	0	1664	0	671
	Cow slaughtered	143	5547	2496	3051	427	99	2525	0	622	0	115	0	1600	0	187
	Last calf slaughtered	154	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Offspring	Cow supported with supplement	32	724	326	398	67	4	327	154				173			
	Weaner supported with supplement	40	3013	1252	1761	245	17	1499	705				795			
	1st calf slaughtered end month	49	6199	2790	3410	519	36	2855	1342				1513			
	Cow slaughtered	143	2509	1129	1380	233	15	1132	532				600			
	Last calf slaughtered	154	4880	2196	2684	396	28	2259	1062				1198			

Source: Model outcomes.

Note: GE = gross energy, DE = digestible energy. ME = metabolisable energy, Maint. = maintenance, Preg. = pregnancy, Lact. = lactation, NE = net energy, MJ = Mega joule.

Table 3b
Proportional distribution of the gross energy intake of the cow and her calves at five different sample months.

		Month	Manure as % of GE	DE as % of GE	Ferment. as % of GE	Urine as % of GE	ME as % of GE	ME as % of DE	Heat loss as % of GE				NE as % of GE			
									Growth	Maint.	Preg.	Lact.	Growth	Maint.	Preg.	Lact.
Cow	Cow supported with supplement	32	42%	58%	6%	1%	51%	87%	0%	9%	0%	8%	0%	22%	0%	12%
	Weaner supported with supplement	40	45%	55%	6%	1%	48%	87%	0%	11%	7%	0%	0%	29%	1%	0%
	1st calf slaughtered end month	49	45%	55%	6%	1%	48%	87%	0%	9%	0%	6%	0%	23%	0%	9%
	Cow slaughtered	143	45%	55%	8%	2%	46%	83%	0%	11%	0%	2%	0%	29%	0%	3%
	Last calf slaughtered	154														
Offspring	Cow supported with supplement	32	45%	55%	9%	1%	45%	82%	21%	0%	0%	0%	24%	0%	0%	0%
	Weaner supported with supplement	40	42%	58%	8%	1%	50%	85%	23%	0%	0%	0%	26%	0%	0%	0%
	1st calf slaughtered end month	49	45%	55%	8%	1%	46%	84%	22%	0%	0%	0%	24%	0%	0%	0%
	Cow slaughtered	143	45%	55%	9%	1%	45%	82%	21%	0%	0%	0%	24%	0%	0%	0%
	Last calf slaughtered	154	45%	55%	8%	1%	46%	84%	22%	0%	0%	0%	25%	0%	0%	0%

Source: Model outcomes.

Note: GE = gross energy, DE = digestible energy, ME = metabolisable energy, Maint. = maintenance, Preg. = pregnancy, Lact. = lactation, NE = net energy, Ferment. = Fermentation.

Table 4a
Distribution of the carbon intake of the cow and her calves at five different sample months.

		month	Gross carbon intake	Carbon in manure	Digestible carbon	Carbon in fermentation and urine	Carbon lost through heat loss	Carbon contained in net energy
			kg C/month					
Cow	**Cow supported with supplement**	32	171.61	64.8	106.80	13.56	29.78	63.46
	Weaner supported with supplement	40	174.24	69.7	104.54	14.02	34.31	56.21
	1st calf slaughtered end month	49	174.24	69.7	104.54	14.02	28.23	62.29
	Cow slaughtered end month after weaning last calf	143	135.65	54.26	81.39	14.02	19.67	47.7
	Last calf slaughtered	154	0	0	0	0	0	0
Offspring	**Cow supported with supplement**	32	17.72	7.09	10.63	1.91	4.1	4.62
	Weaner supported with supplement	40	71.68	27.05	44.64	6.64	17.86	20.14
	1st calf slaughtered end month	49	151.61	60.64	90.97	14.8	35.8	40.37
	Cow slaughtered end month after weaning last calf	143	61.35	24.54	36.81	6.6	14.2	16.01
	Last calf slaughtered	154	119.35	47.74	71.61	11.33	28.33	31.95

Source: Model outcomes.

Table 4b
Proportionate distribution of the carbon intake of the cow and her calves at five different sample months.

		month	Manure-based carbon as % of gross carbon	Digestible carbon as % of gross carbon	Carbon in fermentation and urine as % of gross carbon	Metabolisable carbon as % of digestible carbon	Carbon lost through heat loss as % of gross carbon	Carbon contained in net energy as % of gross carbon
Cow	**Cow supported with supplement**	32	38%	62%	8%	87.3%	17%	37%
	Weaner supported with supplement	40	40%	60%	8%	86.6%	20%	32%
	1st calf slaughtered end month	49	40%	60%	8%	86.6%	16%	36%
	Cow slaughtered end month after weaning last calf	143	40%	60%	10%	82.8%	15%	35%
	Last calf slaughtered	154						
Offspring	**Cow supported with supplement**	32	40%	60%	11%	82.0%	23%	26%
	Weaner supported with supplement	40	38%	62%	9%	85.1%	25%	28%
	1st calf slaughtered end month	49	40%	60%	10%	83.7%	24%	27%
	Cow slaughtered end month after weaning last calf	143	40%	60%	11%	82.1%	23%	26%
	Last calf slaughtered	154	40%	60%	9%	84.2%	24%	27%

Source: Model outcomes.

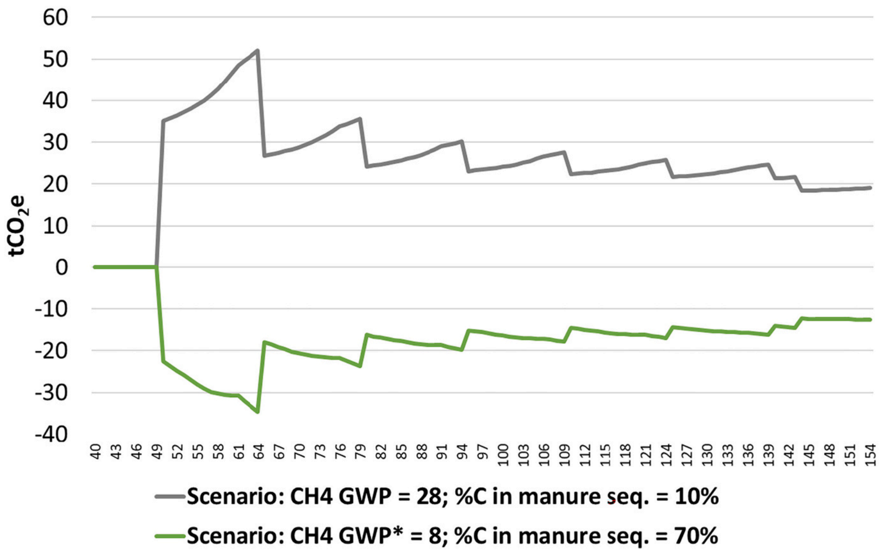


Fig. 3. The ton of GHG, expressed in terms of tCO_2e, per ton meat produced under two scenarios.
Note: A net source of emissions is indicated as a positive value and a net sink by a negative value.
Seq. = sequestered.

Table 5
The distribution of the flow of tCO_2e emissions per ton of meat produced.

	tCO_2e/tmeat					
	Cow: sources of emissions	**Weaner: sources of emissions**	**Cow: sinks contained in net energy**	**Weaner: sinks contained in net energy**	**Manure**	**Net impact**
CH_4 GWP = 28; %C in manure seq. = 10%	23.4	14.5	−11.4	−5.1	−2.3	**19.1**
CH_4 GWP* = 8; %C in manure seq. = 70%	12.4	7.4	−11.5	−5.1	−15.8	**−12.6**

Note: Sources of emissions are indicated as positive values and sinks by negative values.
Seq. = Sequestered.

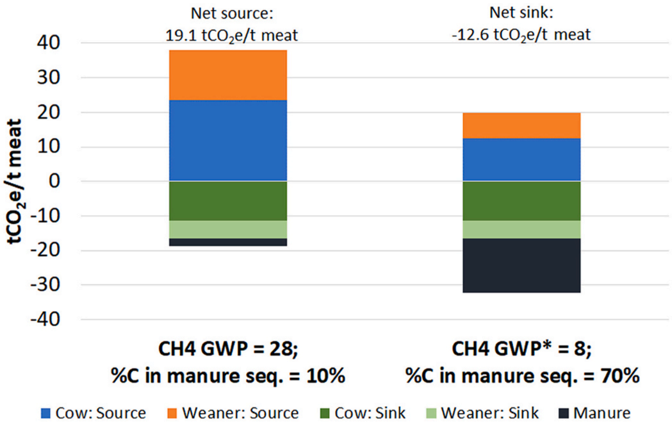


Fig. 4. The distribution of the flow of tCO_2e emissions per ton of meat produced at the end of month 154 under two scenarios.
Note: A source of emissions is indicated as a positive value and a sink by a negative value.
Seq. = sequestered.

5.1. Model approach and implications

It was indicated in Section 1 that there are at least four pathways towards improving GHG mitigation and accelerating sequestration in the beef cattle production sector. They were, in short, the following:

- Increased carbon sequestration from the production of crops and improved rangeland management (this aspect has been addressed with reference to the manure-based carbon sequestration capability of the soil).

Table 6
tCO_2e/ton meat (carcass weight) at month 154 after incorporating the life of the cow and 8 of her calves.

		Carbon in the manure sequestered by the soil		
		10%	**40%**	**70%**
CH_4global warming potential	**8**	0.95	−5.8	−12.6
	28	19.1	12.3	5.6

Note: A net source of emissions is indicated as a positive value and a net sink by a negative value.

- Applying more relevant and recently tested enteric methane estimates and the global warming potential factor for CH_4 (both these aspects have been addressed).
- Applying a comprehensive method of accounting for the GHG emissions inclusive of the animals' contribution to be a carbon sink and not just a source of emissions (which is a major focus of this paper).
- Improved genomic selection, diet manipulation, the use of dietary supplements and rumen modification as well as the need to reduce nitrogen applications, that becomes possible with improved pasture management (these aspects have not been addressed herein).

We used a system dynamics model to model the energy and carbon flows of a cow and her 8 offspring through her life cycle based on a predominantly grass-fed system in South Africa with moderate maize-based supplements at key times during the lives of both the cow and her offspring. We did so while considering the impact of different land management conditions leading to different sequestration rates of the carbon contained in the manure, different global warming potentials of CH_4, and making provision for the carbon embodied in the animals during different physiological stages.

At least three key messages can be distilled from the results. Message one is that the results indicate that the gross carbon intake divides into at least three major carbon streams. The gross carbon intake originates from photosynthesised carbon, a process accelerated by grazing (Wilson et al., 2018), but grazing by itself also avoids the grass becoming moribund and suppresses the risk of emissions through fire. Thus, each photosynthesised carbon molecule is contributing to the removal of carbon from the atmosphere. The first of the three streams contain the carbon that is released into the atmosphere in the short term as CH_4 (see also key message three) and heat (inclusive of losses through respiration). The second and third streams comprise the carbon contained in the manure and embodied in the animals and are between 66% and 76% of gross carbon intake. These two streams, therefore, account for the major portion of the carbon stream. The degree to which the carbon contained in the manure is sequestrated in the soil depends on the health of the soil (Franzluebbers, 2010; Sacks et al., 2014; Conant et al., 2017), which is a result of soil management (Teague et al., 2011; Wang et al., 2015; Shrestha et al., 2020) (see also key message two). The carbon embodied in the animal, the virtual carbon, leads to the protein accumulation in humans and human development in general. Eventually this carbon will return to the soil once the consumer dies and is buried. Currently, both these latter two carbon streams are ignored within the conventional GHG accounting context. Provision for only a portion of the first stream, that of CH_4, is made with the balance (namely of heat loss) being considered as carbon in and carbon out and thus in balance. This accounting bias has had a profound and detrimental impact on the debate with respect to beef cattle production and consumption.

Message two follows from the above, namely that improving soil health through improved land management can accelerate the sequestration of the carbon contained in the plants and the manure lying on the soil surface, as well as carbon exudated from both living and dead plant roots. The emphasis should thus be on stimulating and incentivising prudent land use management practices and not cattle, or herbivory in general, per se. Through biased accounting practices and obscuring the potential of rangeland management towards carbon sequestration, the contribution of prudent cattle management towards reducing GHG emissions and improving soil health have been largely ignored.

Message three pertains to the fact that it matters which GWP for CH_4 is used. While not directly related to a management intervention, the use of a GWP of 8 times that of CO_2 instead of 28 when considering an additional methane load to account for CH_4's much shorter atmospheric lifespan does have an impact on the quantum of emissions to be reduced and the measures to be taken. It will also assist in refocusing the debate towards the main contributor of GHG emissions, namely the energy sector, while re-emphasising the need for and support of proper land use management.

6. Conclusion

The GHG emitted relative to the meat produced varies greatly depending on the global warming potential (GWP) for CH_4, and the degree to which the carbon contained in the manure is sequestered in the soil or not. Recent evidence suggests that the GWP of CH_4 in a 20-year span is much more likely to be about 8 when the addition to the atmospheric load remains constant or is minute than the more commonly accepted 28. Moreover, the healthier the soil, the more manure-based carbon is returned to the soil. This range varies greatly and to derive the maximum benefits from the natural soil-based processes necessitates a strong focus on prudent land use management that prevents erosion and stimulates grass cover to improve soil health. Lastly, carbon embedded in the net retained energy, is also stored within the animal and her additional offspring itself.

Making provision for these factors, it is estimated that the cumulative net emissions after 154 months can be as much as 19 tCO_2e per ton meat produced (carcass weight) over the period when considering a GWP of 28 and 10% sequestration of manure-based carbon. This figure, however, can turn into a net sink of emissions of about 12.6 tCO_2e per ton of meat produced if a GWP of 8 is used and 70% of the carbon in the manure is sequestrated. Thus, under conditions of healthy soils, the net marginal addition of a cow and her calves onto an otherwise stable global herd can lead to a reduction in greenhouse gas emissions. What should be noted is that this figure is conservative as the calculations exclude accelerated carbon sequestration through accelerated grass regrowth and increased litter deposits.

Discussions with respect to the reduction of GHG emissions from livestock must consider the full life cycle of the female animal and her offspring, inclusive of the virtual (or embedded) carbon, the GWP of CH_4, and the condition of the rangelands. Much more effort should therefore be directed towards improving the soil and land use management, including incentive measures and knowledge sharing, as it has a mutually reinforcing impact on the mitigation of GHG emissions and the sequestration of carbon.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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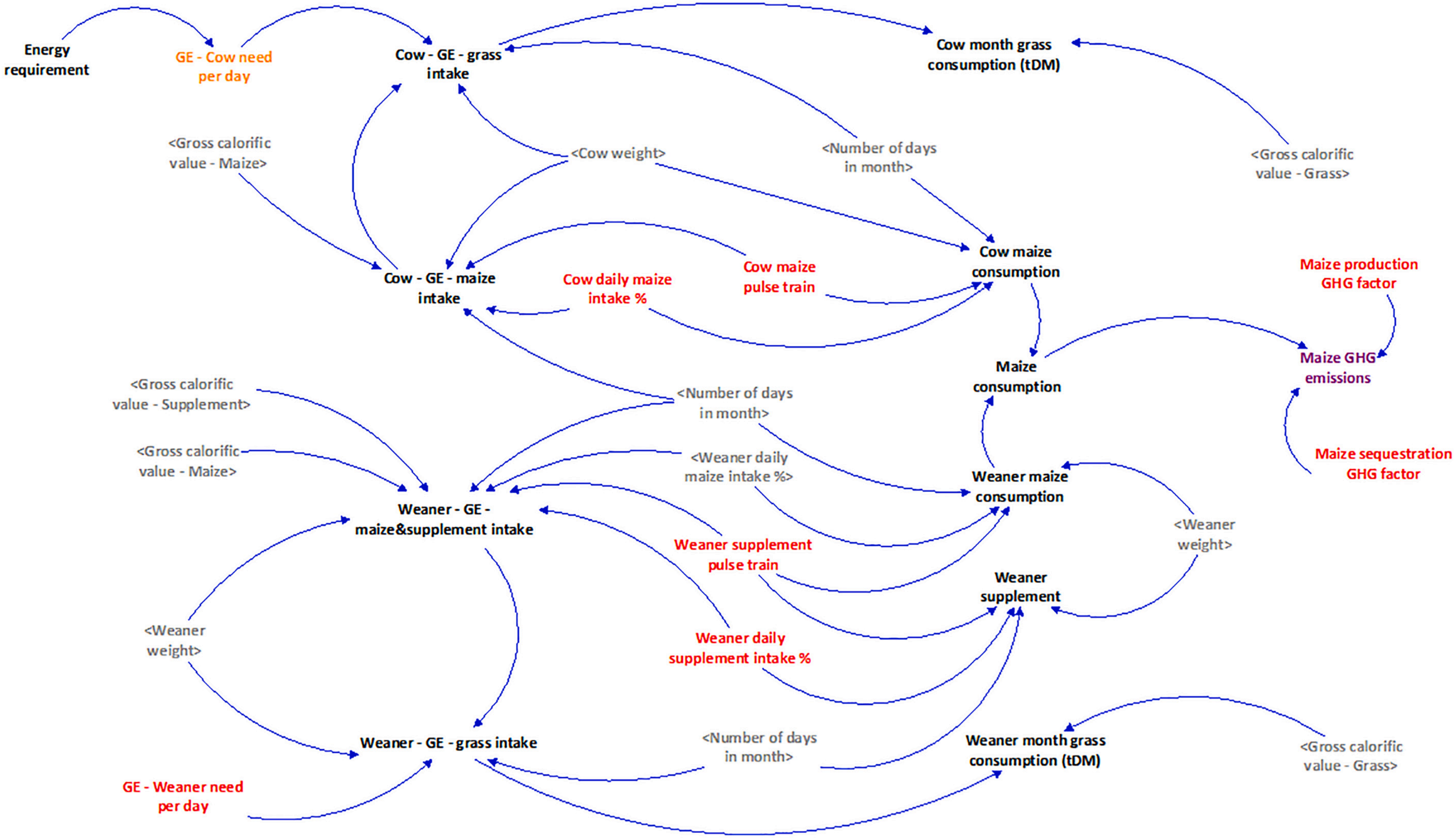
Appendix 1. Feedstock sub-model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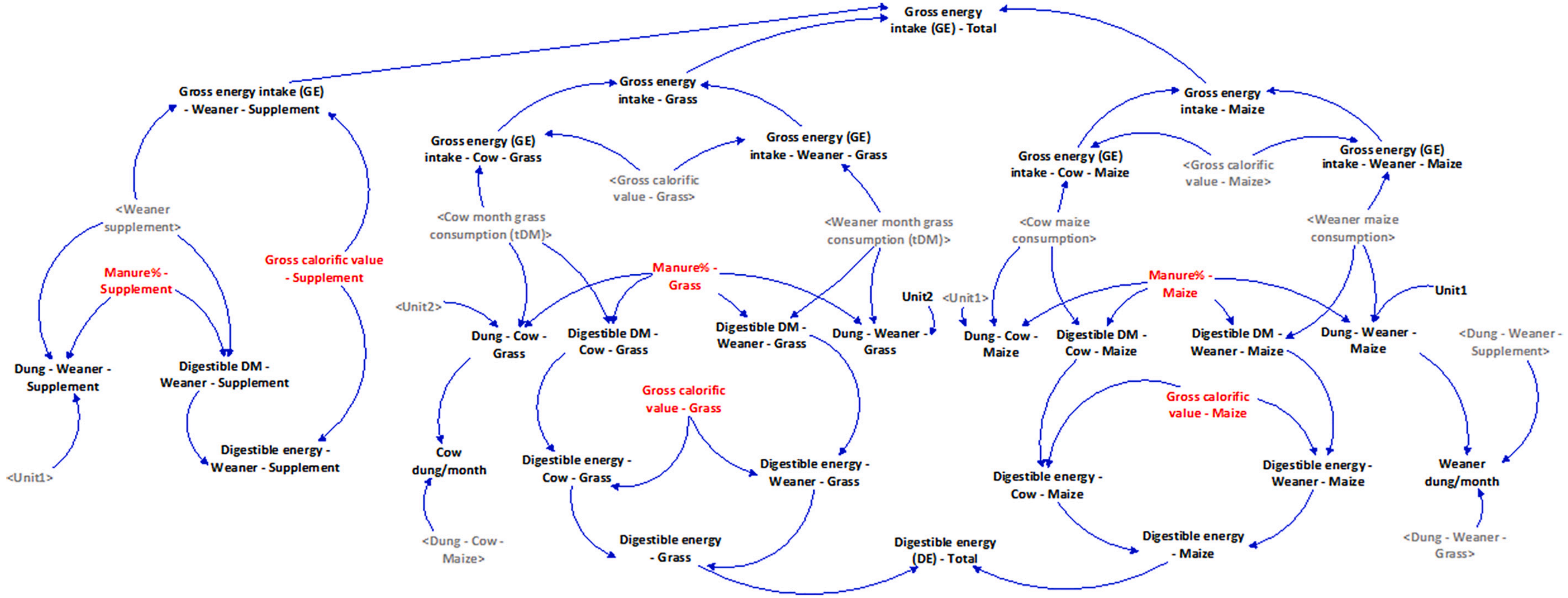
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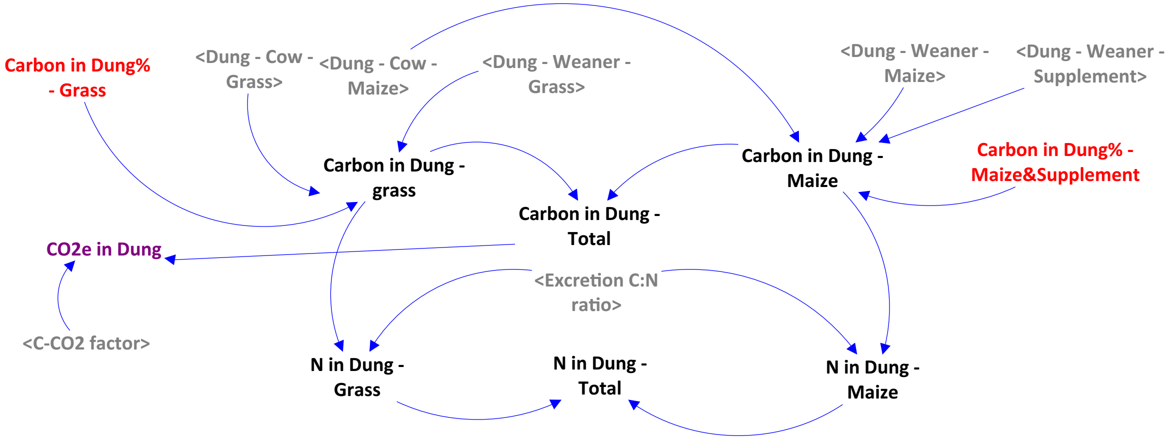
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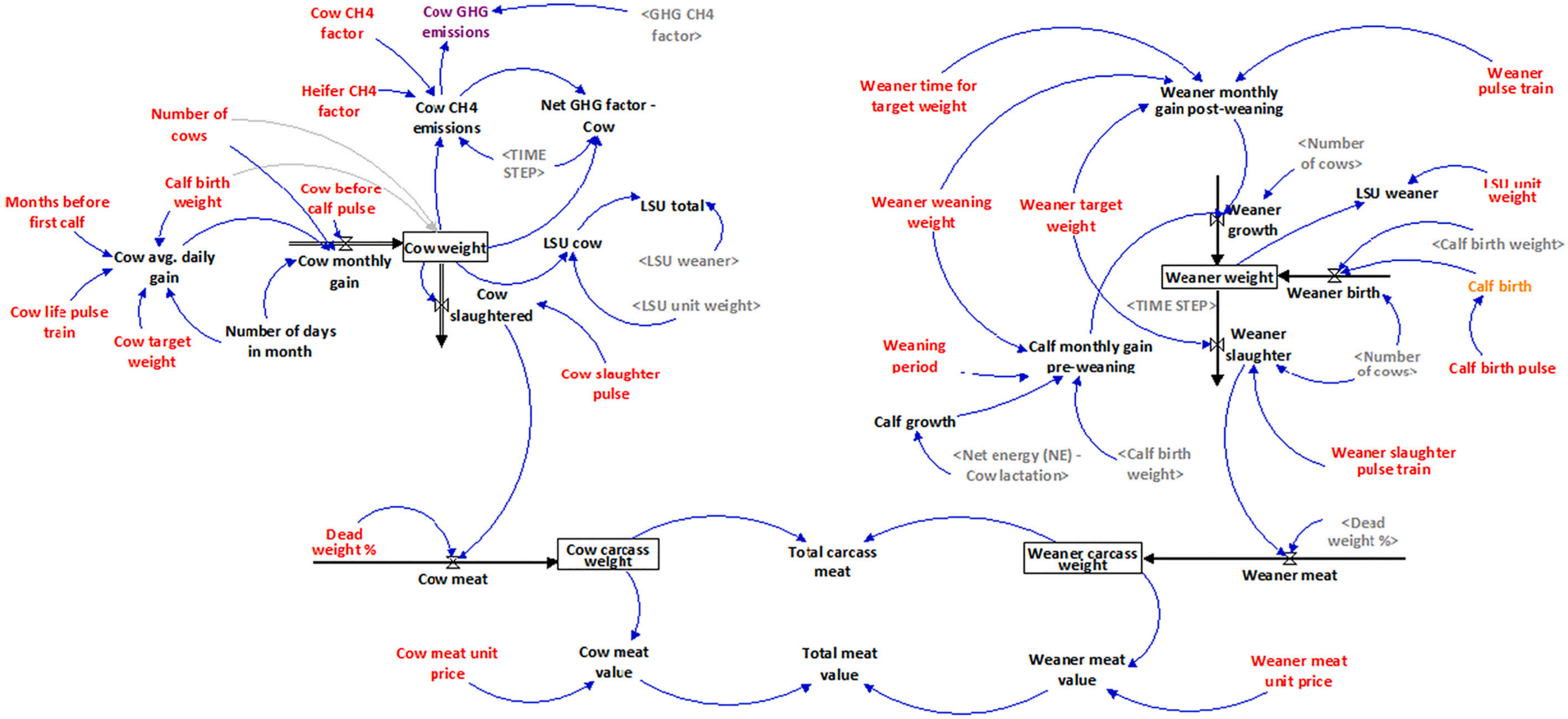
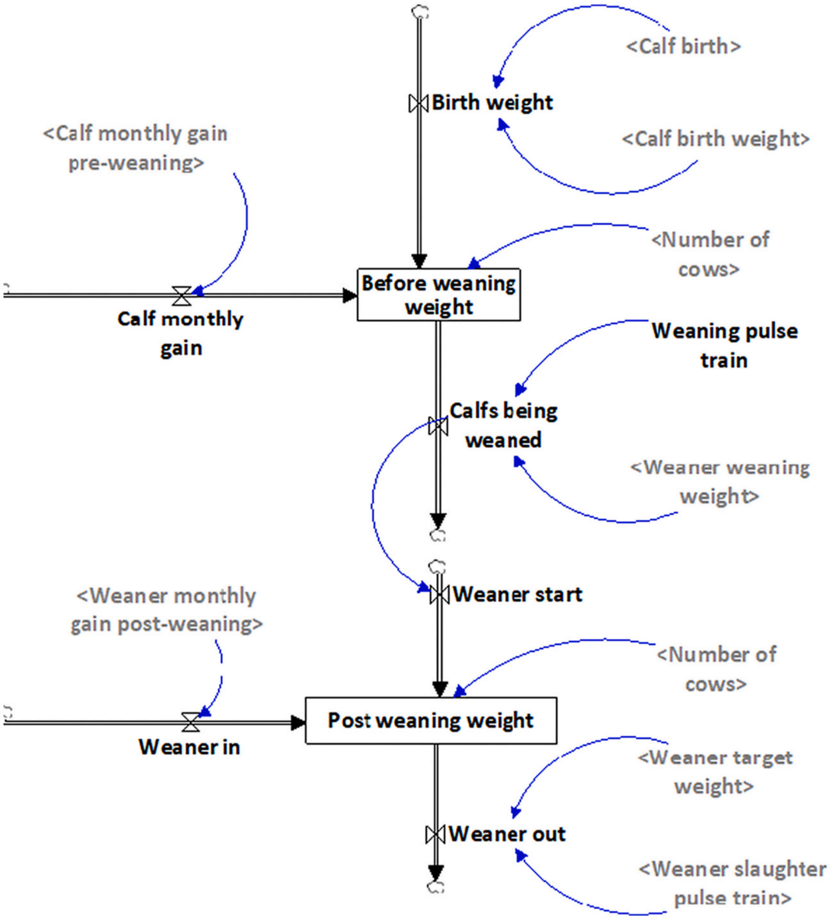
N in Dung - Maize

Appendix 2. Animal production sub-model

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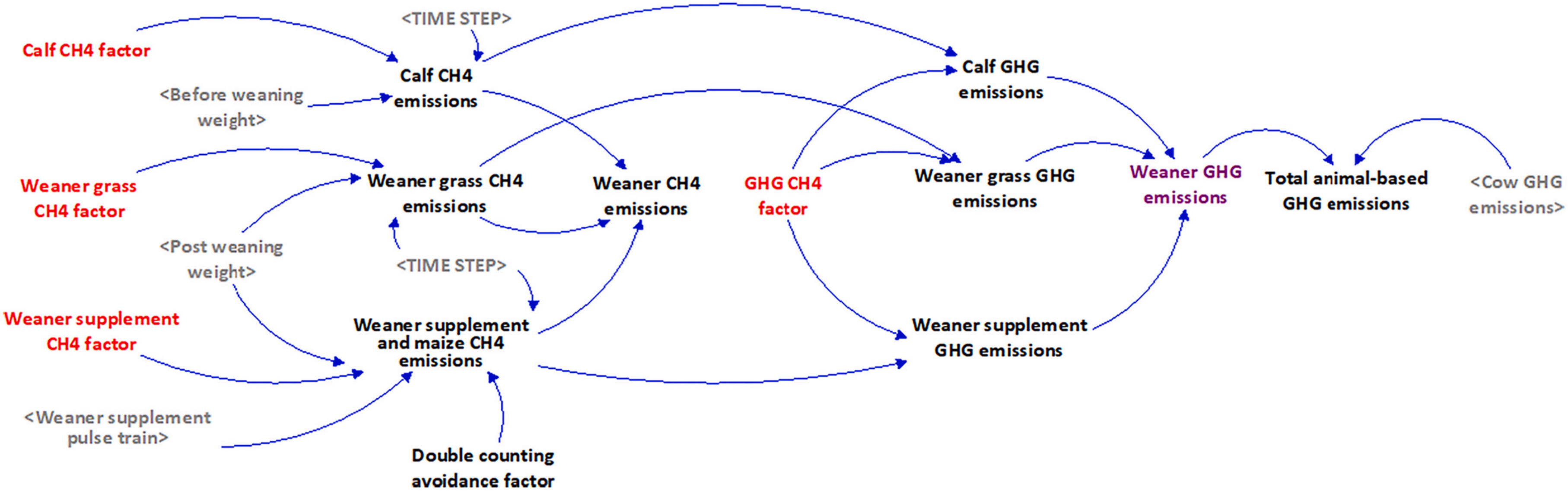
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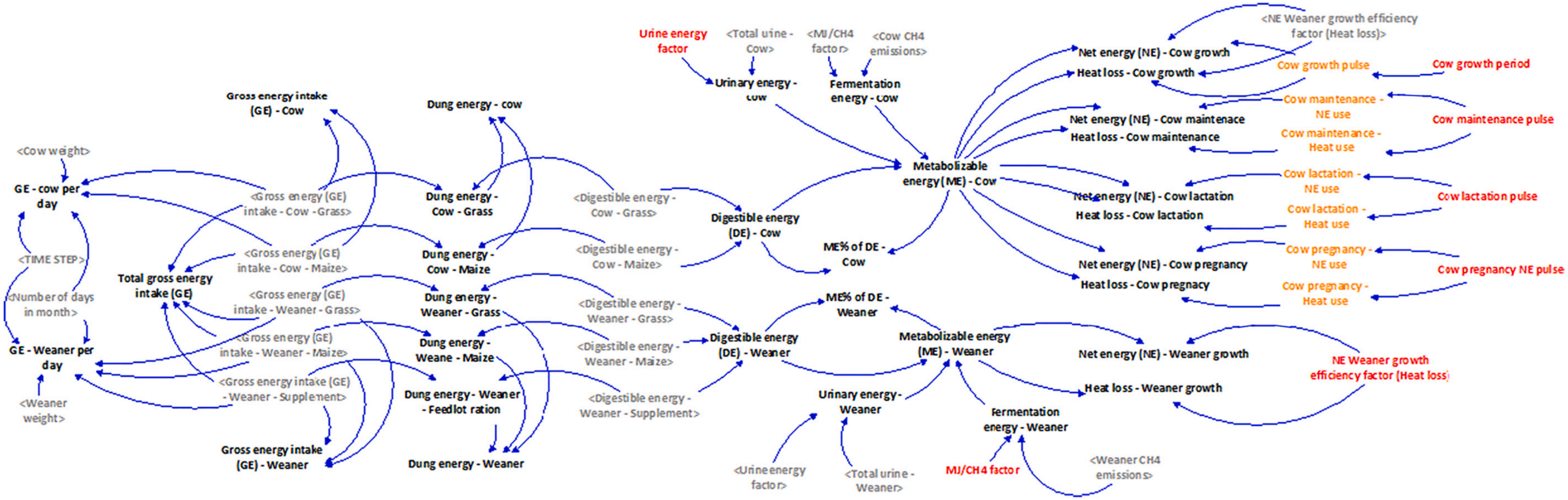
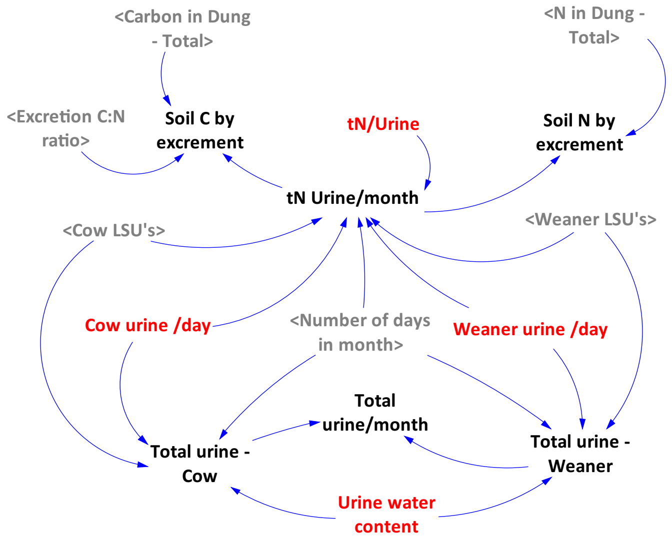
<Before weaning weight>
Calf GHG emissions
Weaner grass CH4 factor
Weaner grass CH4 emissions
Weaner CH4 emissions
GHG CH4 factor
Weaner grass GHG emissions
Weaner GHG emissions
Total animal-based GHG emissions
<Cow GHG emissions>
<Post weaning weight>
<TIME STEP>
Weaner supplement CH4 factor
Weaner supplement and maize CH4 emissions
Weaner supplement GHG emissions
<Weaner supplement pulse train>
Double counting avoidance factor

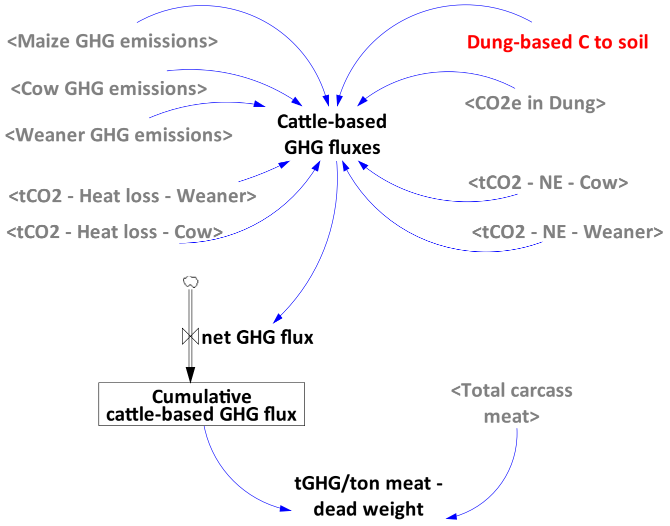
Appendix 3. Energy flow sub-model



Appendix 4. Excrement sub-model



Appendix 5. Greenhouse gas flow sub-model



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