Large-scale pasture restoration may not be the best option to reduce greenhouse gas emissions in Brazil

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Supplementary Material - Figures

**Figure S1.** Beef production (Mt CWE - carcass weight equivalent) and animals finished in feedlots and in semi-confinement (Mhd) in Mato Grosso (ANUALPEC, 2015; IBGE, 2018).
Figure S2. Potential carrying capacity of restored pasture.

Figure S3. Proportion of pasture area to be intensified in Mato Grosso state according to the property sizes.
Figure S4. Average municipality’s beef sale price (US$ kg CWE$^{-1}) for Mato Grosso State. Data provided by Mato Grosso’s Institute of Agricultural Economics by e-mail. These data are for the year of 2014 (US$ = R$ 2.35, average value for 2014).

Figure S5. Animals finished in semi-confinement (Mhd) from 1996 to 2012 and under modeled scenarios. (Though the average growth of steers finished in semi-confinement system is the same for all simulated scenarios (Table 1), it amount less in MIX-FEED and MIX-FEED+ scenarios because in these scenarios, the model prioritizes the steers finishing in feedlot system).
**Figure S6.** Animals finished in feedlot (Mhd) from 1996 to 2012 and under modeled scenarios.

**Figure S7.** Methane enteric emissions intensity (kg CO$_2$e.kgCWE$^{-1}$) and average age at slaughtering (In projected scenarios, it refers to intensified systems).
Figure S8. Beef price for producers. Values are adjusted by IGP-DI index (FGV, 2016).

Figure S9. SimPec equation flowchart. A - Herd module, B - Economic module and C - GHG emissions modules. CO$_2$ emissions from land use change, production, manufacture and transport of animal feeds, fuels, fertilizers, pesticides and other agrochemicals and in the manufacture of the equipment and machinery used in the production systems were calculated outside the model.
Supplementary Material - Tables

**Table S1.** Characterization of pasture degradation levels (Dias-Filho, 2014).

| Pasture stocking rate (AU.ha⁻¹) | Level of degradation | Pasture area (Mha) |
|----------------------------------|----------------------|--------------------|
| up to 0.4                        | High                 | 7.8                |
| from 0.4 to 0.8                  | Moderate             | 7.0                |
| from 0.8 to 1.5                  | Low                  | 7.5                |

**Table S2.** Current and future land use in Mato Grosso under modeled scenarios¹ (thousand ha)

| Current | Projected 2030 |
|---------|----------------|
|         | BASE | MIX-PAST | MIX-FEED | MIX-FEED+ |
| Planted forest | 60 | 63 | 63 | 63 | 63 |
| Soy | 6,265 | 13,182 | 13,184 | 13,195 | 13,220 |
| Corn | 1,923 | 9,548 | 9,559 | 9,675 | 9,945 |
| Sugarcane | 228 | 233 | 233 | 233 | 233 |
| Pastureland | 24,760 | 28,009 | 25,073 | 24,966 | 24,673 |

¹Future land uses come from Soares-Filho et al. (2016) and Rochedo et al. (2018). The BASE scenario assumes an Intermediate Environmental Governance scenario while the other three ones a Strong Environmental Governance scenario from Rochedo et al. (2018). The differences in soy and corn croplands and pastureland between the MIX-intensification scenarios are due to the additional soy-corn cropland area needed to feed the herd (See Table S4). The BASE scenarios assumes the current trend of deforestation, whereas the other three lower rates of deforestation. The resulting pastureland and soy and corn croplands also takes into account additional area needed to feed the herd according to table S4.

**Table S3.** Accumulated and annual Deforestation (Mha) and resultant emissions (MtCO₂) for Mato Grosso according to land use scenarios

| Deforestation | Emissions |
|---------------|-----------|
| 2012-2030 (accumulated) | 2030 | 2012-2030 (accumulated) | 2030 |
| BASE scenario ¹ | 14.4 | 1.01 | 3,863 | 327 |
| Intensification scenarios ² | 8.47 | 0.30 | 1,925 | 83.0 |

¹Soares-Filho et al. (2016).
²Rochedo et al. (2018).

**Table S4.** Additional demand for grains (Mt) and areas for production in the projected scenarios by 2030.

| Scenarios | Grains for herd feedstuff by 2030 (Mt) ³ | Additional area for produce grains for herd feedstuff (Mha) ³ |
|-----------|-----------------------------------------|----------------------------------------------------------|
| BASE      | 0.90 | 0.08 | 0.15 |
| MIX-PAST  | 0.96 | 0.09 | 0.16 |
| MIX-FEED  | 1.61 | 0.13 | 0.28 |
| MIX-FEED+ | 3.04 | 0.23 | 0.53 |

³We assume just the additional demand in relation to the 2012.

In Mato Grosso corn and soy are prevailing produced in double cropping system (sharing the same area). Thus, to estimate the area need to produce grains for herd feedstuff, we use only the more demanded grain (corn), assuming a linear trajectory of increase of productivity from 5,230 to 5,590 kg/ha (MAPA, 2018).

**Table S5.** Structure of operational and investments costs used in the economic module.

| Operational costs | Extensive systems | Improved systems |
|-------------------|-------------------|------------------|
| Labor (head.worker⁻¹) ⁴ | 201 | 422 | 401 |
| Creep feeding ⁴ | | | Table S6 |
| Mineral and protein feeding at pasture | | | Table S6 |

⁴Table S6
Semi-confinement feeding  
Feedlot feeding  
Sanitation management (US$.AU⁻¹.yr⁻¹)  
Extensive pasture maintenance (US$.ha⁻¹.yr⁻¹)  
Improved pasture maintenance (US$.ha⁻¹.yr⁻¹)  
Infrastructure maintenance (US$.ha⁻¹.yr⁻¹)  
Machinery maintenance (US$.ha⁻¹.yr⁻¹)  
Administrative costs and taxes (US$.ha⁻¹.yr⁻¹)  
Other costs (US$.ha⁻¹.yr⁻¹)  

**Investments**  
Pasture restoration (US$.ha⁻¹)  
Feedlot installation (US$. additional confined head⁻¹yr⁻¹)  

US$ = R$ 2.35 (Average value for 2014).  
‡ We assume as small scale properties with area smaller than 500 ha, and large scale those larger or equal to 500 ha.  
To calculate labor cost, we considered the ratio between cattle heads per workers (ANUALPEC, 2015) and the monthly cost per worker of US$ 638 (minimum salary plus taxes).  
ANUALPEC (2015). The costs are converted from US$.AU⁻¹.yr⁻¹ to US$.ha⁻¹.yr⁻¹ using average stocking rate of 0.8 and 1.2 AU.ha⁻¹ for extensive and improved systems, respectively.  
Creep feeding was assumed only in the MIX-FEED+ scenario.  
Rosa and Torres (2009).

**Table S6. GHG emissions, share of components (%), daily intake and cost of nutritional management of animals.**

| Component | Unit cost (US$.kg⁻¹ yr⁻¹) | GHG emissions (kg CO₂e.kg⁻¹ yr⁻¹) | Creep feeding | Mineral supplement | Protein-mineral supplement | Semi-confinement diet | Feedlot diet |
|-----------|--------------------------|---------------------------------|--------------|-------------------|--------------------------|----------------------|-------------|
| Corn grain | 0.10                     | 0.26                            | 89.80        | -                 | 42                       | 88.70                | 45.80       |
| Corn silage | 0.11                     | 0.10                            | -            | -                 | -                        | -                    | 49.45       |
| Soybean meal | 0.40                     | 0.22                            | 6.12         | -                 | 7                        | 6.60                 | 3.09        |
| Urea | 0.59                     | 1.75                            | 2.04         | -                 | 14                       | 2.20                 | 0.62        |
| Calcite limestone | 0.04                     | 0.087                           | -            | -                 | -                        | -                    | 0.30        |
| Mineral salt | 0.68                     | 0.164                           | -            | 100               | -                        | -                    | -           |
| Common salt | 0.26                     | -                               | -            | 25                | -                        | -                    | -           |
| Mineral salt 130g of P | 1.06                     | 0.164                           | -            | 12                | -                        | -                    | -           |
| Mineral nucleus | 1.36                     | 0.164                           | 2.04         | -                 | 2.50                     | 0.74                 |             |

Daily intake (% BW)  
1.00  
0.018  
0.10 (EP)  
0.30 (IP)  
1.40  
2.30  

Cost (US$.kg⁻¹)  
0.14  
-  
0.34  
0.16  
0.13  

US$ = R$ 2.35 (Average value for 2014).  
EP= extensive pasture; IP= improved pasture.  
‡ The composition of diet is obtained from RLM®/Esalq-USP.  
Corn grain and soybean prices – Data provided by Mato Grosso’s Institute of Agricultural Economics through e-mail.  
Corn silage cost – Obtained from ANUALPEC (2015) assuming that the yield is 40 Mg.ha⁻¹ of fresh weights.  
Estimted as Cardoso et al. (2016).  
Mineral salt composition: Dicalcium phosphate – 33.30%; Calcite limestone – 27.75%, Sulfur – 1.00%; Zinc sulfate – 1.30%; Copper sulfate – 0.6%; Manganese sulfate – 1.00%; Cobalt sulfate – 0.030%; Calcium iodate – 0.010%; Sodium selenite – 0.006%; Sodium chloride – 35.00%.  
Common salt: Sodium chloride.  
Mineral 130g of P composition: Dicalcium phosphate – 72.00%; Calcite limestone – 20.11%, Sulfur – 2.00%; Zinc sulfate – 2.60%; Copper sulfate – 1.2%; Manganese sulfate – 2.00%; Cobalt sulfate – 0.060%; Calcium iodate – 0.020%; Sodium selenite – 0.012%.  
Mineral nucleus composition: Dicalcium phosphate – 30.00%; Calcite limestone – 33.00%, Sulfur – 1.92%; Zinc sulfate – 0.70%; Copper sulfate – 0.35%; Manganese sulfated – 0.20%; Cobalt sulfate – 0.023%; Calcium iodate – 0.0076%; Sodium selenite – 0.003%; Sodium chloride – 30%; Phigrow (10%) – 1.70%; Rumensin – 2.1%.  
Expert consultations  
Barbosa et al. (2016).  
Oliveira and Millen (2014).
Table S7. Projections of beef production (Mt CWE) in Brazil (2015-2030) and in Mato Grosso by 2030.

| Year | Brazil  | Mato Grosso |
|------|---------|-------------|
| 2015 | 9.21a   |             |
| 2016 | 9.70a   |             |
| 2017 | 9.84a   |             |
| 2018 | 9.69a   |             |
| 2019 | 10.24a  |             |
| 2020 | 10.52a  |             |
| 2021 | 10.57a  |             |
| 2022 | 10.80a  |             |
| 2023 | 11.19a  |             |
| 2024 | 11.20a  |             |
| 2025 | 11.36a  |             |
| 2026 | 11.60b  |             |
| 2027 | 11.85b  |             |
| 2028 | 12.10b  |             |
| 2029 | 12.36b  |             |
| 2030 | 12.62b  | 2.0c        |

* Brazilian agribusiness projections (MAPA, 2015).
* Projected using the average growth rate of beef production in Brazil by 2015 – 2025.
* From 2009 to 2017 Mato Grosso was responsible for approximately 16% of total beef production in Brazil (IBGE, 2018). We assume the same share by 2030 resulting in a production of 2.0 Mt CWE in Mato Grosso.

Table S8. Management factors for the change in soil organic carbon (SOC) storage due to land use change.

| Land use | Management factors of SOC storage | Uncertainties bounds |
|----------|-----------------------------------|----------------------|
|          |                                   | Upper | Lower |
| Annual crop – No-till (Forest and Cerradão)* | 0.91 | 0.99 | 0.83 |
| Annual crop – No-till (Cerrado)* | 1.04 | 1.11 | 0.97 |
| Degraded pasture b,c | 0.91 | 1.05 | 0.77 |
| Restored pasture b | 1.19 | 1.26 | 1.12 |

* Maia et al. (2010). These authors analyzed results from 96 sampled points and also reviewed results from other studies in the Mato Grosso and Rondônia region. They applied a linear mixed-effect modeling approach to determine the SOC dynamics over 20 years for the land use transition native vegetation (NV) to no-till crops.
* Maia et al. (2009). These authors analyzed results from 63 sampled points and also reviewed results from other studies in the Mato Grosso and Rondônia region. They applied a linear mixed-effect modeling approach to determine the SOC dynamics over 20 years for two land use transitions: native vegetation (NV) to degraded pasture (DP) and native vegetation to improved pasture (IP).
* The degraded pastures to be restored in Mato Grosso are in general older than 20 years (MapBiomas, 2018), hence without further losses of carbon.

Table S9. Sensitivity of Net Present Value (NPV) to changes in prices of inputs to feed supplementation and pasture improvement and of beef sale.

| Variations in input and output prices (%) | NPV (%) |
|------------------------------------------|---------|
|                                          | BASE    | MIX-PAST | MIX-FEED | MIX-FEED+ |
| Inputs - feed supplementation ± 10       | ± 5.7   | ± 7.0    | 5.8      | ± 6.2     |
| Inputs - pasture improvement ± 10        | ± 2.5   | ± 5.2    | ± 3.5    | ± 2.9     |
| Beef sale prices ± 9.2                   | ± 22.3  | ± 25.8   | ± 21.9   | ± 21.1    |

Table S10. Amount of inputs, emissions of GHG and costs of pasture maintenance.

| Machinery services* | Quantity (hour.ha⁻¹)* | Energy (MJ.hour⁻¹)* | CO₂eq (kg.ha⁻¹)* | Unit cost (US$.hour⁻¹)* | Cost (US$.ha⁻¹) |
|---------------------|------------------------|---------------------|-------------------|-------------------------|-----------------|
| Limestone internal transport | 0.01 | 29.3 | 0.02 | 38.28 | 0.54 |
| Limestone distribution | 0.02 | 29.3 | 0.04 | 35.19 | 0.84 |
| Distribution of fertilizer | 0.02 | 29.3 | 0.04 | 38.28 | 0.77 |
## Table S11. Amount of inputs, emissions of GHG and costs of pasture restoration.

| Machinery services a | Quantity (hour.ha\(^{-1}\)) a | Energy (MJ.hour\(^{-1}\)) b | CO\(_2\)eq (kg.ha\(^{-1}\)) b | Unit cost (US\$.hour\(^{-1}\)) a | Cost (US\$.ha\(^{-1}\)) |
|----------------------|-----------------|------------------|-----------------|-----------------|-----------------|
| Heavy harrow disc operation | 1.31 | 29.3 | 2.81 | 43.79 | 57.34 |
| Intermediary harrow disc operation | 0.88 | 29.3 | 1.89 | 43.79 | 38.53 |
| Leveler harrow disc operation | 1.08 | 29.3 | 2.32 | 39.04 | 42.16 |
| Limestone internal transport | 0.07 | 29.3 | 0.15 | 38.28 | 2.68 |
| Limestone distribution | 0.12 | 29.3 | 0.26 | 35.19 | 4.22 |
| Distribution of fertilizer at planting | 0.02 | 29.3 | 0.04 | 38.28 | 0.77 |
| Fertilization after planting | 0.13 | 29.3 | 0.28 | 35.19 | 4.57 |
| Sowing | 0.13 | 29.3 | 0.28 | 35.19 | 4.57 |
| Seed compaction | 0.31 | 29.3 | 0.67 | 26.64 | 8.26 |
| Fertilizer internal transport | 0.31 | 29.3 | 0.67 | 35.19 | 10.74 |
| **Sub-total** | | | | **9.36** | **173.90** |

| Labor a | Quantity (hour.ha\(^{-1}\)) a | Unit cost (US\$.hour\(^{-1}\)) a | Cost (US\$.ha\(^{-1}\)) |
|---------|-----------------|-----------------|-----------------|
| Limestone distribution | 0.12 | 3.46 | 0.42 |
| Fertilizer distribution | 0.15 | 3.46 | 0.52 |
| Sowing | 0.15 | 3.46 | 0.52 |
| Internal transport | 0.14 | 3.46 | 0.48 |
| Fertilization after planting | 0.15 | 3.46 | 0.52 |
| **Sub-total** | | | **2.87** |
of pasture restoration varies according to the gap yield of pasture.

We assume this dose of fertilizer for each increase of 1 AU.ha⁻¹. Then, the total cost of pasture restoration varies according to the gap yield of pasture.

**Table S12. Parameters for calculating GHG emissions**

| Parameter | Value |
|-----------|-------|
| MK – Milk production (kg.day⁻¹) | 3.70³ |
| MF – Milk fat content (%) | 3.50³ |
| MP - Milk protein content (%) | 3.20³ |
| Nfert – nitrogen fertilizer (kg.ha⁻¹) | Table S10:S11 |
| C_lm - Limestone added to soil (kg ha⁻¹) | Table S10:S11 |
| Bo - Maximum CH₄-producing capacity (m³ CH₄.kg of volatile solid excreted⁻¹) | 0.10⁹ |
| MCF - Methane conversion factor for manure management (%) | 1.50³ |
| UE - Urinary energy (%GE) | 0.04³ |
| ASH - Ash content of manure (% dry matter intake) | 0.08⁹ |
| Fvol_u - N fertilizer (other sources) that volatilizes (kg N vol. kg N applied⁻¹) | 0.10³ |
| FPvol - N deposited by grazing animals that volatilizes (kg N vol. kg N excreted⁻¹) | 0.20³ |
| FFvol - N deposited by feedlot animals that volatilizes (kg N vol. kg N excreted⁻¹) | 0.30³ |
| FR_lch - N added to soils leached (kg N leached. kg of N) | 0.30³ |
| EF_lch - Emission factor from N leached (kg N₂O N .kg N leached⁻¹) | 0.0075³ |
| EF_vol - Emissions from atmospheric deposition of N on soils and water surfaces (kg N₂O N kg N volatilized⁻¹) | 0.01³ |
| EFDfert - Direct emissions from fertilizers (kg N₂O N kg N applied⁻¹) | 0.10³ |
| EFd - Direct emissions from dung deposited in pasture (kg N₂O N kg N excreted⁻¹) | 0.014 (WS); 0 (DS)⁹ |
| EFu - Direct emissions from urine deposited in pasture (kg N₂O N kg N excreted⁻¹) | 0.0193 (WS); 0.0001 (DS)⁹ |
| EFm - Factor for direct N₂O emissions from manure management (kg N₂O-N. kg N⁻¹) | 0.02³ |
| EFCO₂ - Carbon emission from urea (kg C. kg urea⁻¹) | 0.20³ |
| EF_lm - Carbon emission from limestone (kg C. kg limestone⁻¹) | 0.13³ |
| Fvol_u - N fertilizer (urea) that volatilizes (kg N vol. kg N applied⁻¹) | 0.30³ |

WS= wet season; DS = dry season.

¹ Expert consultation
² IPCC (2006)
³ MCTI (2014)
⁴ Lessa et al. (2014)

**Table S13. Properties of animal diet in different feeding regimes**

|          | Extensive pasture | Improved pasture | Semi-confinement | Feedlot |
|----------|------------------|------------------|------------------|---------|
| Crude protein concentration (%) | 7.6³ | 8.8⁹ | 18.5³ | 13.9⁴ |
| Digestibility of dry matter (%) | 50.0⁹ | 55.3⁹ | 65.8⁶ | 71.4⁷ |
| Methane conversion rate (%) | 6.5⁶ | 6.0⁹ | 4.0⁹ | 3.0⁶ |

³Paulino et al. (2005)
⁹Euclides et al. (2009).
⁸ Barbosa et al. (2016).
⁷Cota et al. (2014).
Supplementary Material – Notes

The SIMPEC model (the acronym for Simulação de Sistemas de Produção da Pecuária de Corte) simulates the dynamics of a complete beef production cycle, which includes cow-calf, backgrounding, and fattening operations at selected spatial units, e.g. from an individual ranch up to a cluster of ranches distributed at municipal or regional level. Although partial cycle systems, in which individuals specialize on one component of the cycle, are also common, the interaction between these systems at a regional scale can be aggregated to a single cycle. SIMPEC calculates the costs and returns of improving pasture management and herd health and fertility, or adopting supplemental feeding for animals at pasture or in feedlot, required to attain a pre-determined series of production or policy targets (i.e. pasture restoration extent, zootechnical parameters, meat production). These targets are used to compare and contrast a range of intensification scenarios. The model calculates the impact of each scenario on herd growth and age distribution, beef volume and productivity, net revenues, and associated GHG emissions.

Supplementary Material - Methods

Definition of dry and wet season

We assume the beginning of dry season when the forage water demand is not adequately supplied by available water in the soil. To define it, we perform the soil water balance (Thornthwaite and Mather, 1955) by assuming maximum available soil water capacity of 100 mm and estimating evapotranspiration of grass from average monthly temperature (Camargo et al., 1999). Average monthly temperature and total monthly precipitation are obtained from WorldClim (Hijmans et al., 2005) and Brazilian Geological service (Pinto et al., 2011), respectively.

Estimation of CO₂ emissions from land use change and CO₂ sequestration from pasture restoration

To estimate the change of SOC (soil organic carbon) stocks, we use the method of comparing C stocks after land use and/or management change relative to the carbon stock in a reference condition (IPCC, 2003), as follow:

\[ \Delta C = \frac{C_{ref} \times [F_{c_t_0} - F_{c_t_1}]}{D} \]

where \( \Delta C \) is the annual change of carbon stock in the reservoir (Mg C/yr); \( C_{ref} \) is the carbon stock in the soil of native vegetation (Mg C); \( F_{c_t} \) is the stock change factor in the moment \( t \) (dimensionless); and \( D \) is the time dependence of stock change factors which is the default time period for transition between equilibrium SOC values (years), here we use the IPCC default time of 20 years (IPCC, 2006).

The reference carbon (\( C_{ref} \)), was reproduced by the methodology of Bernoux et al. (2002). The stock change factor (\( F_{c_t} \)), which represents the gain or loss of carbon for \( D \) period in the top soil (0-30 cm), is the result of the multiplication of a set of factors as: i) the change factor for land use (\( F_{lu} \)), which means the carbon change according land
use system (crop cultivation or pasture, in the particular case of this study); ii) the factor of management (Fmg) (tillage/no-tillage and degraded/improved pastures); iii) the factor of inputs (Fi), which reflects the adoption or not of inputs as irrigation, fertilization, liming and others. The above soil stock change equation was applied in a spatially explicit manner, pixel by pixel, for Mato Grosso State by laying the reference soil carbon stock map over the Otimizagro simulated land use and management maps. We use regional specific factors derived for the states of Rondônia and Mato Grosso, which include portions of the Amazon and Cerrado biomes (Table S8).

Sensitivity analyses

To account for uncertainty in the economic outputs, we allow a ± 10% variation in prices of input for feed supplementation (including mineral, protein and energetic feed supplementation for animals at pasture as well as diet of animals in feedlot regime) and pasture improvement (fertilizers and seeds). Since beef price is a key variable in the determination of profit, we also include a range of ± 9.2% in beef sale prices, which mimics the observed price trends from 1997 to 2016 (Figure S10).

To include uncertainty bounds in our GHG estimates, we consider the lower and upper bounds of variation of SOC reported in Maia et al. (2009; 2010) (Table S8).

Supplementary Material - Equations

The equations below are for simulating the herd dynamics, economics of ranching and GHG emissions. The relationships between equations are depicted in Figure S9.

Herd dynamic module

The herd dynamic is simulated monthly covering the full cycle of the whole herd from birth of the calves to mature animals ready for slaughter. The model seeks to maintain stocking rate and carrying capacity of pasture as close as possible by altering previously the amount of cows and bulls in the herd. As we do not assume any purchase of animals, the model separates heifers and steers from the herd to reproductive purposes when needed. The System Carrying Capacity (SCC) is estimated as follows:

$$\text{SCC}_{s,m,t} = [\text{SR}_{s,m,t} \times (\text{Pa}_{s,m,t} - \text{Pa}_{\text{ref},s,m,t})] + [\text{SR}_{\text{imp}} \times \text{Pa}_{\text{ref},s,m,t}]$$  \hspace{1cm} (eq. S1)

where SCC is the system carrying capacity in total animal units (AU). s is the management scenario, m the municipality, and t is the time in months. SR is the stocking rate for extensive pasture (in AU ha⁻¹). Pa is the total pasture area (ha). Pa_ref is improved pasture area (ha). SR_imp is the stocking rate for improved pasture (AU ha⁻¹). SCC is updated every 12 months. When SCC is greater than pasture stocking rate, the model separates more heifers and steers from the herd to reproductive purposes discard cows and bulls when SCC is lower, discard old cows and bulls.

The number of animals in the herd is updated monthly according to eq. S2.

$$\text{Q}_{s,m,t} = \sum_{c} \left(\text{Q}_{c,s,m,t-1} + \text{N}_{s,m,t} - \text{M}_{s,m,t} - \text{V}_{c,s,m,t}\right)$$  \hspace{1cm} (eqS2)
where \( Q \) refers to the number of animals in the herd. \( s \) is the management scenario, \( m \) the municipality, \( t \) is the time in months and \( c \) animal categories (1 = cows, 2 = bulls, 3 = male calves, 4 = female calves, 5 = steers on extensive pasture, 6 = heifers on extensive pasture, 7 = steers on improved pasture, 8 = heifers on improved pasture, 9 = steers in semi-confinement and 10 = steers in feedlot). \( N \) is the number of animal births. \( M \) is the number of animal deaths and \( V \) is the number of animals sold for slaughter.

Every 12 months, the herd size is adjusted as a function of \( SSc \) by altering the number of cows. 

\[
Q_{c=1,s,m,t} = Q_{c=1,s,m,t} + \left[ \left( \frac{Cw}{100} \times SCC_{s,m,t} \times 450}{Wu} - Q_{c=1,s,m,t} \right) \times \theta a_t \right] \quad (eq. S3)
\]

where \( Q_{c=1} \) is the number of cows in the herd. \( s \) is the management scenario, \( m \) the municipality, and \( t \) is the time in months. \( Cw \) refers to average percentage of the herd composed by cows (it is previously defined by the model that seeks to fit \( SSC \) and pasture stocking rate). \( SCC \) is the system carrying capacity in total animal units (AU) \( (eq. S1) \).\( Wu \) refers to the average weight of adult cows (kg) \( (Table 1) \) and \( \theta a_t \) is the cow adjustment constant \( (\theta a_t= 1 \ \text{for the month when the model updates the number of cows and} \ \theta a_t= 0 \ \text{for others}) \). To increase the number of cows, the model allocates heifers able to enter in reproductive phase according to pre-defined age. The model also replaces senile cows every 12 months according to the replacement rate of cows \( (Table 1) \). The discarded animals are thus sold to slaughter. The number of bulls is given by bull/cow ratio \( (Table 1) \). Every 12 months, new animals enter in the herd as follow.

\[
N_{s,m,t} = Q_{c=1,s,m,t} \times \frac{\tau n_t}{100} \times \theta b_t \quad (eq. S4)
\]

where \( N \) is the number of animal birth. \( s \) is the management scenario, \( m \) the municipality, and \( t \) is the time in months. \( Q_{c=1} \) is the number of cows in the herd. \( \tau n \) refers to birth rate \( (\%) \) \( (Table 1) \) and \( \theta b \) is the birth constant \( (\theta b= 1 \ \text{for the month when birth takes place and} \ \theta b= 0 \ \text{for others}) \). We assume that animals are born in august, of which 50% is male and 50% female.

The model also account the mortality of animals in the herd as follow:

\[
M_{s,m,t}= Q_{s,m,t-1} \times \frac{\tau m}{100} \times 12 \quad (eq. S5)
\]

where \( M \) is the number of animal deaths. \( s \) is the management scenario, \( m \) the municipality, and \( t \) is the time in months. \( Q \) refers to the number of animals in the herd \( (eq. S2) \) and \( \tau m \) denotes the mortality rate \( (\%) \) \( (Table 1) \).

The individual weight of animals is updated monthly according to eq. S6.

\[
W_{c,s,m,t} = W_{c,s,m, \ t-1} + 30 \times ADG_{c,s,t} \quad (eq. S6)
\]

where \( W \) refers to the live weight of animals (kg). \( c \) is the animal categories, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( ADG \) denotes average daily gain \( (kg.animal^{-1}.day^{-1}) \). For \( c = 1 \) (cows) and \( c = 2 \) (bulls), when \( W \) is equal to the weight of adult cows and bulls \( (Table 1) \), respectively, \( ADG \) is 0. For \( c = 3 \)
(male calves) and \( c = 4 \) (female calves) in the suckling phase, \( ADG \) is calculated according to eq. S7 and for others animal category, it is pre-defined in Table 1.

\[
ADG_{c,s} = \left( \frac{W_w - W_b}{A_w \times 30} \right)
\]

(eq. S7)

where \( ADG \) denotes average daily gain (kg\,animal\(^{-1}\),day\(^{-1}\)). \( c \) is the animal categories and \( s \) is the management scenario. \( W_b \) and \( W_w \) denotes the weight of animals at birth and at weaning (kg) respectively, while \( A_w \) refers to the age at weaning (months) (Table 1).

**Economic module**

To estimate the economic performance, the model computes the investments and operational costs and the resultant revenues. The revenues are calculated as follow:

\[
RV_{s,m,t} = \sum_c \left( V_{c,s,m,t} \times W_{c,s,m,t} \times CDP_c \times P_{c,m,t} \right)
\]

(eq. S8)

where \( RV \) refers to revenue from the sale of animals (US$). \( s \) is the management scenario, \( m \) the municipality, \( t \) is the time in months and \( c \), animal category. \( V \) is the number of animals sold, \( W \) refers to the live weight of animals (kg) (eq. S6), \( CDP \) is the Carcass Dressing Percentage (%) (Table 1) and \( P \), the beef sale price (US$/kg\(^{-1}\)) (Figure S4).

In that way, the cash flow is updated monthly according to eq. S9.

\[
Cf_{s,m,t} = RV_{s,t} - Oc_{s,m,t} - Iv_{s,t}
\]

(eq. S9)

where \( Cf \) denotes the cash flow (US$). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( RV \) refers to revenue from the sale of animals (US$) (eq. S8), \( Oc \) is the operational costs (US$) (Table S5) and \( Iv \) is the investment costs (pasture restoration and feedlot installation costs) (US$) (Table S5).

By the difference between revenues and operational costs, the model calculates the profit margin as follow:

\[
Pm_{s,m,t} = RV_{s,m,t} - Oc_{s,m,t}
\]

(eq. S10)

where \( Pm \) refers to profit margin (US$). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( RV \) refers to revenue from the sale of animals (US$) (eq. S8) and \( Oc \) are the operational costs (US$) (Table S5).

To estimate the economic feasibility of investments for intensification of production, the model calculates the Net Present Value, according to eq. S11.

\[
NPV_{s,m} = \sum_{t=1}^{n} \frac{(RV-Iv-Oc)_{s,m,t}}{\left(1 + \frac{r}{100}\right)^t}
\]

(eq. S11)

where \( NPV \) is the net present value (US$). \( s \) is the management scenario, \( m \) the municipality, \( t \) is the time in months and \( n \) is the number of months of simulation. \( RV \) refers to revenue from the sale of animals (US$) (eq. S8), \( Iv \) is the investment costs
(pasture restoration and feedlot installation costs) (US$) (Table S5), Oc is the operational costs (US$) (Table S5) and r is the rate of return, which we assume 8.5 %.

**GHG module**

**CH₄ emissions from enteric fermentation**

The enteric emissions of methane are calculated according to IPCC’s tier 2 (IPCC, 2006), as follow:

\[
N_{Em_{c,s,m,t}} = C_f \times W_{c,s,m,t}^{0.75} \times Q_{c,s,m,t}
\]

(eq. S12)

where \(N_{Em}\) is the net energy required for maintenance animal (MJ day\(^{-1}\)). \(c\) is the animal category, \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(C_f\) is a coefficient which value is 0.386 for lacting cows and 0.322 for other group of animals. \(W\) refers to the live weight of animals (kg) (eq. S6) and \(Q\) refers to the number of animals in the herd (eq. S2).

\[
N_{Ea_{c,s,m,t}} = C_c \times W_{c,s,m,t} \times Q_{c,s,m,t}
\]

(eq. S13)

where \(N_{Ea}\) denotes the net energy for animal activity (MJ day\(^{-1}\)). \(c\) is the animal category, \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(C\) corresponds to animal’s feeding coefficient (\(C= 0.37\) for animals in extensive pasture, \(C= 0.17\) for animals in improved pastures and \(C= 0\) for animals in feedlot and in semi-confinement). \(W\) refers to the live weight of animals (kg) (eq. S6) and \(Q\) refers to the number of animals in the herd (eq. S3).

\[
N_{El_{s,m,t}} = MK \times (1.47 + 0.40 \times MF) \times Q_{c=1,s,m,t} \times \theta_l
\]

(eq. S14)

where \(N_{El}\) is the net energy for lactation (MJ day\(^{-1}\)). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(MK\) is the amount of milk produced (kg.animal\(^{-1}\).day\(^{-1}\)) (Table S12), and \(MF\) refers to the fat content of milk (%) (Table S12). \(Q_{c=1}\) is the number of cows in the herd and \(\theta_l\) is the lactation constant (\(\theta_l= 1\) for the months when cows are lactating and \(\theta_l= 0\) for others).

\[
N_{Ep_{s,m,t}} = Q_{c=1,s,m,t} \times 0.10 \times N_{Em_{c=1,s,m,t}} \times \theta_p
\]

(eq. S15)

where \(N_{Ep}\) is the net energy required for pregnancy (MJ day\(^{-1}\)). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(Q_{c=1}\) is the number of cows in the herd (eq. S3). \(N_{Em}\) is the net energy required for cow’s maintenance (eq. S12). \(\theta_p\) is the pregnant constant (\(\theta_p= 1\) for the months when cows are pregnant and \(\theta_p= 0\) for others).

\[
N_{Eg_{c,s,m,t}} = 22.02 \times \left(\frac{W_{c,s,m,t}}{C \times W_u}\right)^{0.75} \times ADG_{c,s,t}^{1.097} \times Q_{c,s,m,t}
\]

(eq. S16)

where \(N_{Eg}\) refers to the net energy needed for growth (MJ day\(^{-1}\)). \(c\) is the animal category, \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(W\) refers to the live weight of animals (kg) (eq. S6). \(ADG\) denotes the average daily weight gain of
animals (kg.animal\(^{-1}\).day\(^{-1}\)) (Table 1, eq. S7) and \(Q\) is the number of animals in the herd (eq. S2).

\[
REM_c = 0.298 + 0.00335 \times \text{DE}_c \quad \text{(eq. S17)}
\]

where \(REM\) is the ratio of net energy available in a diet for maintenance to digestible energy consumed (dimensionless). \(c\) is the animal category and \(DE\) denotes digestible energy expressed as a percentage of gross energy (% GE) (Table S13).

\[
REG_c = -0.036 + 0.00535 \times \text{DE}_c \quad \text{(eq. S18)}
\]

where \(REG\) is the ratio of net energy available for growth in a diet to digestible energy consumed (dimensionless). \(c\) is the animal category and \(DE\) denotes digestible energy expressed as a percentage of gross energy (% GE) (Table S13).

**CH\(_4\) emissions from manure**

Methane emissions from manure are calculated according IPCC’s tier 2 (IPCC, 2006), as follow:

\[
V_{s,c,s,m,t} = \left[ \text{GE}_{c,s,m,t} \times \left( 1 - \frac{\text{DE}_c}{100} \right) + \left( \text{UE} \times \text{GE}_{c,s,m,t} \right) \right] \times \left[ \left( 1 - \frac{\text{ASH}}{18.45} \right) \right] \quad \text{(eq. S21)}
\]

where \(V_s\) is the daily volatile solid excreted (kg dry matter animal\(^{-1}\) day\(^{-1}\)). \(c\) is the animal category, \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(GE\) denotes the gross energy (MJ animal\(^{-1}\) day\(^{-1}\)) (eq. S19). \(DE\) is the digestible energy expressed as a percentage of gross energy (% GE) (Table S13). \(UE\) is the urinary energy expressed as fraction of GE (Table S12) and ASH is the ash content of manure calculated as a fraction of the dry matter feed intake (Table S12).

\[
\text{Efman}_{c,s,m,t} = V_{s,c,s,m,t} \times \text{Bmax} \times 0.67 \times \frac{\text{MCF}}{100} \times 30 \quad \text{(eq. S22)}
\]

where \(\text{Efman}\) is the methane emission factor of manure (kg CH\(_4\).animal\(^{-1}\)). \(c\) is the animal category, \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(V_s\) is the daily volatile solid excreted (kg dry matter animal\(^{-1}\) day\(^{-1}\)) (eq. S21). \(\text{Bmax}\) refers to maximum methane producing capacity for manure (m\(^3\) CH\(_4\) kg\(^{-1}\) of VS excreted) (Table S12). The factor 0.67 is used to convert m\(^3\) CH\(_4\) to kg CH\(_4\) and \(\text{MCF}\) is the methane conversion factors for manure management system (%) (Table S13).

\[
\text{CH}_4\text{man}_{s,m,t} = \sum_c \text{Efman}_{c,s,m,t} \times Q_{c,s,m,t} \quad \text{(eq. S23)}
\]

where \(\text{CH}_4\text{man}\) refers to methane emissions from herd manure (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months and \(c\), animal category. \(\text{Efman}\) denotes the methane emission factor of manure (kg CH\(_4\).animal\(^{-1}\)) (eq. S22) and \(Q\) refers to the number of animals in the herd (eq. S2).

**N\(_2\)O emissions from manure**
Nitrous oxide emissions from manure are calculated according IPCC’s tier 2 (IPCC, 2006), as follow:

\[ \text{NEma}_c = \text{REM}_c \times 18.45 \times \frac{\text{DE}_c}{100} \quad (\text{eq. S24}) \]

where \( \text{NEma} \) is the net energy concentrate of diet (Mj.kg\(^{-1}\)). \( c \) is the animal category. \( \text{REM} \) is the ratio of net energy available in a diet for maintenance to digestible energy consumed (dimensionless) (eq. S17). \( \text{DE} \) denotes digestible energy expressed as a percentage of gross energy (% GE) (Table S13).

For animals in growth stage, \( \text{DMI} \) is calculated as follow:

\[ \text{DMI}_{c,s,m,t} = \left[ \frac{(0.2444 \times \text{NEma}_c - 0.0111 \times \text{NEma}_c^2 - 0.472)}{\text{NEma}_c} \right] \times W_{c,s,m,t}^{0.75} \quad (\text{eq. S25}) \]

where \( \text{DMI} \) is the dry matter intake (kg). \( c \) is the animal category, \( m \) the municipality and \( t \) is the time in months. \( \text{NEma} \) is the net energy concentrate of diet (Mj.kg\(^{-1}\)) (eq S.24). \( W \) refers to the live weight of animals (kg) (eq. S6).

For \( c=1 \) (cows) and \( c=2 \) (bulls), \( \text{DMI} \) is calculated as follow:

\[ \text{DMI}_{c,s,m,t} = W_{c,s,m,t}^{0.75} \times \left[ \frac{(0.0119 \times \text{NEma}_c^2 + 0.1938)}{\text{NEma}_c} \right] \quad (\text{eq. S26}) \]

where \( \text{DMI} \) is the dry matter intake (kg). \( c \) is the animal category, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{NEma} \) is the net energy concentrate of diet (Mj.kg\(^{-1}\)) (eq S.24). \( W \) refers to the live weight of animals (kg) (eq. S6).

\[ \text{NI}_{c,s,m,t} = \text{DMI}_{c,s,m,t} \times \text{CP}_c \times \frac{1}{6.25} \times Q_{c,s,m,t} \times 30 \quad (\text{eq. S27}) \]

where \( \text{NI} \) denotes the total N intake (kg). \( c \) is the animal category, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{DMI} \) is the dry matter intake (kg) (eq S25:S26). \( \text{CP} \) is the protein content in diet of animals (%) (Table S13) and \( Q \) refers to the number of animals in the herd (eq. S2).

\[ \text{Nex}_{c,s,m,t} = \text{NI}_{c,s,m,t} - \left( Q_{(c=1,s,m,t)} \times \text{MK} \times \frac{\text{MP}}{100} \right) - 0.025 \times \text{ADG}_{c,s,t} \quad (\text{eq. S28}) \]

where \( \text{Nex} \) is the total N excretion from manure (kg). \( c \) is the animal category, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{NI} \) denotes the total N intake (kg) (eq. S27). \( Q_{c=1} \) is the number of cows in the herd (eq. S3). \( \text{MK} \) is the amount of milk produced (kg.animal\(^{-1}\).day\(^{-1}\)) (Table S12). \( \text{MP} \) is the protein content in milk (%) (Table S12). \( \text{ADG} \) denotes average daily gain (kg.animal\(^{-1}\).day\(^{-1}\)) (Table 1, eq. S7).

The ratio of N excreted in urine and dung were calculated by eq. S29 according to Scholefield et al. (1991).
\[ \text{Nex}_d = \frac{\text{Nex}}{\left( (1 + 1.2725) \times \frac{\text{CP}_c}{6.25} \right)^{-1.09}} \]  

(eq. S29)

where \( \text{Nex}_d \) refers to N excretion in dung of animals (kg). \( c \) is the animal category, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{Nex} \) is the total N excretion from manure (kg) (eq. S28) and CP is the protein content in animal diet (%) (Table S13). The factor 6.25 converts amount of protein to amount of N.

\[ \text{Nex}_u = \text{Nex} - \text{Nex}_d \]  

(eq. S30)

where \( \text{Nex}_u \) refers to N excretion in urine of animals (kg). \( c \) is the animal category, \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{Nex} \) is the total N excretion from manure (kg) (eq. S28). \( \text{Nex}_d \) refers to N excretion in dung of animals (kg) (eq. S29).

\[ \text{N}_2\text{Omp}_d = \sum_c \left( \text{Nex}_d \times \text{EF}_d + \text{Nex}_u \times \text{EF}_u \times \frac{44}{28} \right) \]  

(eq. S31)

where \( \text{N}_2\text{Omp}_d \) is the direct N\(_2\text{O} \) emissions from the manure of grazing animals (kg). \( s \) is the management scenario, \( m \) the municipality, \( t \) is the time in months and \( c \), the animal category. \( \text{Nex}_d \) refers to N excretion in dung of animals (kg) (eq. S29). \( \text{EF}_d \) is the emission factor for direct N\(_2\text{O} \) emissions from dung (kg N\(_2\text{O}_\text{N} \cdot \text{kg N excreted}^{-1}) \) (Table S12). \( \text{Nex}_u \) is to N excretion in urine of animals (kg) (eq. S30) and \( \text{EF}_u \) is the emission factor for direct N\(_2\text{O} \) emissions from urine (kg N\(_2\text{O}_\text{N} \cdot \text{kg N excreted}^{-1}) \) (Table S12). The factor 44/28 converts N\(_2\text{O}_\text{N} \) to N\(_2\text{O} \) emissions.

\[ \text{N}_2\text{Omp}_i = \sum_c \left[ \left( \text{Nex}_c \times \text{FPvol} \times \text{EF}_{\text{vol}} \right) + \left( \text{Nex}_c \times \text{FR}_{\text{lch}} \times \text{EF}_{\text{lch}} \times \frac{44}{28} \right) \right] \]  

(eq. S32)

where \( \text{N}_2\text{Omp}_i \) is the indirect N\(_2\text{O} \) emissions from the manure of grazing animals (kg). \( s \) is the management scenario, \( m \) the municipality, \( t \) is the time in months and \( c \), the animal category. \( \text{Nex} \) is the total N excretion from manure (kg) (eq. S28). \( \text{FPvol} \) denotes the fraction of N excreted in pastures that volatilize (NH\(_3\)–N + NO\(_x\)–N. kg N Excreted\(^{-1}) \) (Table S12). \( \text{EF}_{\text{vol}} \) is the emission factor of N\(_2\text{O} \) from volatized N (kg N\(_2\text{O}_\text{N} \cdot \text{kg NH}_3\text{–N + NO}_x\text{–N volatilized}) \) (Table S12). \( \text{FR}_{\text{lch}} \) is the fraction of N excreted that leaches (kg NH\(_3\)–N + NO\(_x\)–N. kg N Excreted\(^{-1}) \) (Table S12). \( \text{EF}_{\text{lch}} \) is the emission factor for N\(_2\text{O} \) emissions from N leaching and runoff, kg N\(_2\text{O}_\text{N} \cdot \text{kg N leached and runoff}) \) (Table S12). The factor 44/28 converts N\(_2\text{O}_\text{N} \) to N\(_2\text{O} \) emissions.

\[ \text{N}_2\text{Omp} = \text{N}_2\text{Omp}_d + \text{N}_2\text{Omp}_i \]  

(eq. S33)

where \( \text{N}_2\text{Omp} \) is the nitrous oxide emissions from manure of the grazing animals (kg). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( \text{N}_2\text{Omp}_d \) is the direct N\(_2\text{O} \) emissions from the manure of the grazing animals (kg) (eq. S31) and \( \text{N}_2\text{Omp}_i \) is the indirect N\(_2\text{O} \) emissions from the manure of the grazing animals (kg) (eq. S32).
\[ N_2\text{Omc}_{d\_s,m,t} = Nex_c = 10_{s,m,t} \times Q_c = 10_{s,m,t} \times EFm \times \frac{44}{28} \] (eq. S34)

where \( N_2\text{Omc\_d} \) is the direct nitrous oxide emissions from manure of the animals under feedlot (kg). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( Nex_{c=10} \) is the total N excretion from manure of animals under feedlot (kg) (eq. S28). \( Q_{c=10} \) is the number of steers finished in feedlot and \( EFm \) is the direct \( N_2O \) emission factor for manure management (Kg \( N_2O\)-N kg N\(^{-1}\)) (Table S12). The factor 44/28 converts \( N_2O_N \) to \( N_2O \) emissions.

\[ N_2\text{Omc\_i\_s,m,t} = \left[ \frac{Nex_c = 10_{s,m,t} \times Q_c = 10_{s,m,t} \times (FFvol \times EF\_vol + FR\_lch \times EF\_lch) \times 44/28}{44/28} \right] \] (eq. S35)

where \( N_2\text{Omc\_i} \) is the indirect nitrous oxide emissions from manure of the animals under feedlot (kg). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( Nex_{c=10} \) is the total N excretion from manure of animals under feedlot (kg) (eq. S28). \( Q_{c=10} \) is the number of steers finished in feedlot. \( FFvol \) denotes the fraction of N from manure that volatilizes as NH\(_3\) and NO\(_x\) (kg NH\(_3\)-N + NO\(_x\)-N. kg N Excreted\(^{-1}\)) (Table S12). \( EF\_vol \) is the emission factor for \( N_2O \) from N that volatilize (kg \( N_2O\)-N (kg N volatilized)) (Table S12). \( FR\_lch \) denotes the fraction of N from manure that leaches (kg \( N_2O\_N \), kg N excreted\(^{-1}\)) (Table S12). \( EF\_lch \) denotes the emission factor for \( N_2O \) from N that leaches (kg \( N_2O\)-N (kg N leaching/runoff)) (Table S12). The factor 44/28 converts from \( N_2O_N \) to \( N_2O \) emissions.

\[ N_2\text{Omc\_s,m,t} = N_2\text{Omc\_d\_s,m,t} + N_2\text{Omc\_i\_s,m,t} \] (eq. S36)

where \( N_2\text{Omc} \) is the nitrous oxide emissions from manure of the animals under feedlot (kg). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( N_2\text{Omc\_d} \) is the direct nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S34) and \( N_2\text{Omc\_i} \) is the indirect nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S35).

\[ N_2\text{Oman\_s,m,t} = N_2\text{Omp\_s,m,t} + N_2\text{Omc\_s,m,t} \] (eq. S37)

where \( N_2\text{Oman} \) is the total nitrous oxide emissions from manure of the herd (kg). \( s \) is the management scenario, \( m \) the municipality and \( t \) is the time in months. \( N_2\text{Omp} \) is the nitrous oxide emissions from manure of the grazing animals (kg) (eq. S33) and \( N_2\text{Omc} \) is the nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S36).

\textbf{\( N_2O \) emissions from fertilizer}

Nitrous oxide emissions from synthetic fertilizer are calculated as proposed by IPCC’s tier 2 (IPCC, 2006). In Brazil, urea is the main source of N fertilizer, which presents larger losses of N due to volatilization, especially when applied onto soil surface. We consider the adaptation proposed by MCTI (2014), wherein the \( N_2O \) emission factor from N fertilizer applied as urea is 0.30, while for N fertilizer applied as other sources is 0.1 (IPCC, 2006). Here we assume 100% of N fertilizer comes from urea.
\[
N_2O_{fert,s,m,t} = Pa_{ref,s,m,t} \times Nfert_{s,m,t} \times EF_{Fert} \times \frac{44}{28}
\]  
(eq. S38)

where \(N_2O_{f} \) is the direct \(N_2O\) emission from synthetic fertilizer applied in soil (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(Pa_{ref}\) refers to pasture area restored (ha). \(Nfert\) is the amount of N synthetic fertilizer applied in the soil (kg.ha\(^{-1}\)) (Table S12). \(EF_{Fert}\) refers to direct \(N_2O\) emission factor from N synthetic fertilizer applied in soil (kg \(N_2O - N\) kg \(N\) applied\(^{-1}\)) (Table S12). The factor 44/28 converts \(N_2O - N\) to \(N_2O\) emissions.

\[
N_2O_{fert,s,m,t} = \left( Pa_{ref,s,m,t} \times Nfert_{s,m,t} \times \left[ \frac{Fvol_u + Fvol_o}{2} \times EF_{vol} \right] + FR_{lch} \times EF_{lch} \right) \times \frac{44}{28}
\]  
(eq. S39)

where \(N_2O_{f} \) is the indirect \(N_2O\) emission from synthetic fertilizer applied in soil (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(Pa_{ref}\) refers to pasture area restored (ha). \(Nfert\) is the amount of N synthetic fertilizer applied in the soil (kg.ha\(^{-1}\)) (Table S12). \(Fvol_u\) denotes the fraction of N synthetic applied in soil as fertilizer in urea that volatilize (kg \(NH_3 - N\) + \(NO_x - N\). kg N applied\(^{-1}\)) (Table S12). \(Fvol_o\) denotes the fraction of N synthetic applied in soil as fertilizer in other sources that volatilize (kg \(NH_3 - N\) + \(NO_x - N\). kg N applied\(^{-1}\)) (Table S12). \(EF_{vol}\) is the emission factor of \(N_2O\) from volatized N (kg \(N_2O - N\) (kg \(NH_3 - N\) + \(NO_x - N\) volatilized)\(^{-1}\)). \(FR_{lch}\) denotes the fraction of N synthetic applied in soil as fertilizer that leaches (kg \(N_2O - N\). kg N applied\(^{-1}\)) (Table S12). \(EF_{lch}\) denotes the emission factor for \(N_2O\) from N that leaches (kg \(N_2O - N\) (kg N leaching/runoff)\(^{-1}\)) (Table S12). The factor 44/28 converts \(N_2O - N\) to \(N_2O\) emissions.

\[
N_2O_{fert,s,m,t} = \left( N_2O_{f} + N_2O_{i,s,m,t} \right) \times \theta_{f_t}
\]  
(eq. S40)

where \(N_2O_{fert}\) refers to total \(N_2O\) emissions from synthetic fertilizer (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(N_2O_{f}\) is the direct \(N_2O\) emission from synthetic fertilizer applied in soil (kg) (eq S.38). \(N_2O_{i}\) is the indirect \(N_2O\) emission from synthetic fertilizer applied in soil (kg) (eq. S39). \(\theta_f\) is the fertilizer constant (\(\theta_f = 1\) for the month when fertilizer application take place—it happens once every 12 months—and \(\theta_f = 0\) for others).

**CO\(_2\) emissions from fertilizer**

The \(CO_2\) emissions from limestone and urea applied in soil is calculated as proposed by IPCC’s Tier 1 (IPCC, 2006) as follow:

\[
CO_2_{u,s,m,t} = Pa_{ref,s,m,t} \times Nfert_{s,m,t} \times EF_{CO_2u} \times \frac{44}{12}
\]  
(eq. S41)

where \(CO_2\) refers to \(CO_2\) emissions from N synthetic fertilizer applied in soil as urea (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(Pa_{ref}\) refers to pasture area restored (ha). \(Nfert\) is the amount of N synthetic fertilizer applied in soil (kg.ha\(^{-1}\)) (Table S12). \(EF_{CO_2u}\) is the \(CO_2\) emission factor for urea applied as N.
fertilizer (kgC.kg urea\(^{-1}\)) (Table S12). The factor 44/12 converts from CO\(_2\)C to CO\(_2\) emissions.

\[
CO_2Lm_{s,m,t} = \left[ C_{Lm_{s,m,t}} \times \left( Pa_{ref_{s,m,t}} - Pa_{ref_{s,m,t-1}} \right) \times EF_{Lm} \right] \times \frac{44}{12} \times \theta c_t
\] (eq. S42)

where \(CO_2Lm\) refers to CO\(_2\) emission from limestone applied in soil (kg). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(C_{Lm}\) is the amount of limestone applied in soil (kg ha\(^{-1}\)) (Table S12). \(Pa_{ref}\) refers to pasture area restored (ha). \(EF_{Lm}\) denotes the limestone emission factor (kg C.kg de limestone\(^{-1}\)) (Table S12). The factor 44/12 converts m CO\(_2\)C to CO\(_2\) emissions. \(\theta c\) is the limestone constant (\(\theta c=1\) for the month when limestone is applied— it happens once every 12 months— and \(\theta c=0\) for others).

**CO\(_2\) sequestration**

Explained in the section “Estimation of CO\(_2\) emissions from land use change and CO\(_2\) sequestration from pasture restoration” of supplementary material. (eq. S43)

**GHG budget**

\[
CO_{2e_{s,m,t}} = \left[ (CH_4_{ent} + CH_4_{man})_{s,m,t} \times GWP_1 + (N_2O_{man} + N_2Ofert)_{s,m,t} \right] \times GWP_2 + CO_2Lm_{s,m,t} + CO_2 u_{s,m,t} - CO_2_{soil_{s,m,t}}
\] (eq. S44)

where \(CO_{2e}\) is the GHG budget (kg CO\(_2\)e). \(s\) is the management scenario, \(m\) the municipality and \(t\) is the time in months. \(CH_4_{ent}\) is the methane enteric emissions (kg) (eq. S20). \(CH_4_{man}\) refers to methane emissions from herd manure (kg) (eq. S23). \(N_2O_{man}\) is the total nitrous oxide emissions from manure of the herd (kg) (eq. S37). \(N_2Ofert\) refers to total N\(_2\)O emissions from synthetic fertilizer (kg) (eq. S40). \(CO_2Lm\) refers to CO\(_2\) emission from limestone applied in soil (kg) (eq. S42). \(CO_2 u\) refers to CO\(_2\) emissions from N synthetic fertilizer applied in soil as urea (kg) (eq. S41). \(CO_2_{soil}\) is the carbon sequestration by improved pastures (kg) (eq. S43). \(GWP_1\) and \(GWP_2\) is the global warming potential for methane and N\(_2\)O, 28 and 265 respectively (Myhre et al., 2013).
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