Annex: Potential GHG Emissions and Carbon Sequestration (D3.2, Ch 9)

1.1 Background and Objective

The climate change vulnerability assessment of the local livestock herding systems revealed that several emerging environmental issues in the Bayantumen Soum had been rooted or intensified due to the recent changes in local and regional climates. These issues included: an increase in livestock population and herd size; change in livestock herd mixture; reduction in livestock movements or herders' immobility across the landscape; and migration of unregistered livestock into the area. As a result, the number of livestock in the *soum* has exceeded the grazing capacity of the pastures by 2.8 times and plant communities in a reference or non-degraded state have decreased and dominated by annual and less desirable plant communities. These changes have negatively affected the livelihood and livestock farming of local herders and raised environmental concerns over the rising rate of GHG emissions from both livestock and rangeland degradation.

The Mongolian traditional livestock herding, which significantly relies on native rangelands and pastures, plays an important role in GHG emission and mitigation. Livestock in traditional herding systems produce GHGs directly through enteric fermentation during their digestive process (mainly methane or CH4) and decomposing dung and urine deposited by them on pastures (both nitrous oxide or N2O and methane). However, indirect soil Carbon Dioxide (CO2) and nitrous oxide emissions from grazing intensification and haymaking or production of supplementary livestock feed and fodder are considered relatively larger sources of GHG emissions from livestock farming practices. If well managed, the natural grasslands that livestock grazes on have a large capacity to remove or store those GHGs and prevent them from being emitted into the atmosphere. For example, grasslands are well-recognized as natural carbon sinks, sequestering substantial amounts of atmospheric carbon dioxide in the form of organic carbon in their soils. Therefore, in addition to supporting herders' livelihoods, natural grasslands and rangelands play a vital role in mitigating climate change across Mongolia.

In Mongolian traditional herding systems, livestock is raised on pastures year-round and is mainly grass-fed and finished. Grass-fed livestock raised in pastures typically produce more methane in their lifetime than livestock raised in feedlot operations. Ingestion of grass forage and hay naturally emit more methane than high-quality feed provided to livestock in the feedlot. Also, methane emissions from grass-fed and pasture-based livestock happen over a longer time as they typically reach the market weight more slowly than livestock raised in feedlots (see **Error! Reference source not found.** in Section 4). However, from a carbon footprint standpoint, this comparison may be misleading as net GHG emissions can be potentially much lower in pasture-based livestock production systems that are sustainably managed. Much of the carbon footprint of feedlot livestock is associated with growing grain and high-quality forages and comes from land cultivation and the use of fossil-fuel-based agricultural inputs like fertilizers and pesticides. Conversely, pasture-based livestock herding systems are multifunctional and deliver multiple environmental services (See **Error! Reference source not found.** iin Section 6), including mitigating GHG emissions through carbon sequestration services.

Grazing pressure is frequently mentioned as a driver of land degradation across Mongolia. The widespread overgrazing has raised alarming concerns about the environmental sustainability of current livestock herding practices under a changing climate. High grazing intensity shifts pasture vegetation composition towards less desirable plant communities. This lowers pasture forage availability and quality, reduces livestock productivity and performance, and intensifies GHG emissions per unit of live weight gain by livestock (e.g., through a lower rate of forage intake and digestibility and a higher rate of energy consumption and livestock disease in degraded pastures). In addition, overgrazing limits potential carbon sequestration in pastures and accelerates carbon loss from soil by increasing erosion and deterioration of soil structure, particularly soil aggregates, that physically protect organic matter accumulation in the soil. Therefore, optimizing the stocking rates (e.g., through herd restructuring and removal of less productive livestock) and distribution of livestock grazing (e.g., rotational grazing) is critical to fully benefit from the GHG mitigation capacity of natural grasslands and traditional livestock herding practices in Mongolia.

Several key steps must be taken to reverse rangeland degradation trends and restore the GHG mitigation capacity of traditional livestock herding in Mongolia. Among the recommended mitigation pathways to decrease GHG emissions along the livestock value chain in Mongolia, the primary livestock and pasture management practices include:

- supporting the stocking rates that are in line with pasture carrying capacity
- restructuring livestock herds and improving feeding practices and herd productivity
- promoting seasonal pasture rotations and traditional four-season nomadic rotational grazing
- rehabilitating vegetation and enhancing soil carbon sequestration and GHG mitigation capacity in degraded rangeland.

A preliminary GHG emissions and carbon sequestration assessment was conducted to demonstrate the identification and potential adaption of the above-mentioned livestock and pasture management measures for promoting climate-resilient livestock herding practices in the Bayantumen Soum, a district of Dornod province. Specifically, direct GHG emissions by livestock were compared between the current or traditional livestock herding practices and livestock production under improved life cycles and herd structures. In addition, indirect GHG removal through carbon sequestration in pasture soils was assessed under grazing and pasture management practices resulting from improved livestock life cycles and herd structures. Details of the examined livestock and pasture management practices and their outcomes for GHG emission and removal are explained below.

1.2 Potential GHG Emissions

A life cycle assessment approach covering livestock production up to where the cattle and sheep meat products leave the farm (i.e., cradle to farmgate) was used to estimate direct GHG emissions from local livestock farming practices in the *soum*. This mainly included GHG emissions from enteric fermentation and livestock waste. Conservatively, rangeland carbon stores were considered static, and no grazing and haymaking-induced carbon equivalent emission and loss from rangeland soils was assumed. A similar assumption was made for cultivated soil as animal feed and fodder production in the *soum* (i.e., mainly oat, barley, and wheat) is supposed to be limited to the existing cultivated lands (i.e., no land conversion) and typically with minimum use of fossil-fuel-based agricultural inputs.

Primarily, the effects of the alternative life cycle (as illustrated in Section 4) and cattle herd and sheep flock restructuring scenarios for an average herder household (as explained in Section 5) were investigated. This assessment was then further extended by considering GHG emission reduction effects from improved grazing and pasture management (i.e., reduced grazing pressure, rotated grazing, and rehabilitated pasture vegetation and soil) and livestock productivity practices (i.e., improved feeding efficiency, breeding and mortality rate, and livestock care management). Horses and goats were excluded from this assessment, as currently, there is no working market for their meat products.

The overall GHG emissions were estimated using the reported emission intensity factors for different livestock types and production practices. Relevant previous studies and existing GHG assessment tools (e.g., GLEAM and LEAP) were reviewed to obtain realistic uncertainty ranges (i.e., min and max) of GHG emission intensity or kg of carbon dioxide equivalents (CO2e) per head of adult livestock per year. This included GHG emission intensities for cattle and sheep meat production under grass-fed or grass-finished (i.e., mainly raised and fattened on pastures) and mixed operation (i.e. raised and fattened on a combination of pastures and creep feeding or feedlots), as well as under improved grazing and pasture, and livestock productivity management (see Table A1 in Appendix).

The information on GHG emission intensity was then integrated with information on cattle herds and sheep flocks for an average herder household. This includes herd composition, total herd size based on adult cows and sheep, final live weight of sold livestock, and slaughter age (see sections 4 & 5). The rate (kgCO2e/kg live weight) and total annual CO2e emissions (tCO2e/yr) from the current herd and under the proposed cattle and sheep herd restructuring scenarios were then estimated and compared (Table 1). All estimates were obtained by assuming an average climate and livestock-marketing year and based on the best available data from open-access studies and datasets.

Table 1. GHG emissions from current and alternative cattle herd structure and operation scenarios (Note: The green color indicates GHG removal and red means additional GHG emissions)

Cattle Herd Management*	Operation*	GHG Emission							
		Total (tCO2e/yr)		Rate (kgCO2e/kg live weight)		Change in Total (tCO2e/yr)		Change in Rate (kgCO2e/kg live weight)	
		Min	Max	Min	Max	Min	Max	Min	Max
Current (20 adult cows)	Traditional	122	169	27	38	-	-	-	-
Restructured (40 adult cows)	Cow-calf	109	151	12	17	-13	-18	-15	-21
	Grass-finished	161	223	13	18	39	54	-14	-20
	Feedlot-finished	145	201	8	11	23	32	-19	-26
	Cow-calf	76	139	8	15	-46	-30	-19	-22

Cattle Herd Management*	Operation*	GHG Emission							
		Total (tCO2e/yr)		Rate (kgCO2e/kg live weight)		Change in Total (tCO2e/yr)		Change in Rate (kgCO2e/kg live weight)	
		Min	Max	Min	Max	Min	Max	Min	Max
Restructured & grazing/pasture improved	Grass-finished	113	205	9	16	-9	36	-18	-21
	Feedlot-finished	101	184	6	11	-21	15	-21	-26
Restructured & livestock productivity improved	Cow-calf	94	137	10	15	-28	-32	-17	-23
	Grass-finished	139	203	11	16	17	34	-16	-22
	Feedlot-finished	101	176	6	10	-21	7	-22	-28

* More information in sections 4 & 5

The results of GHG emissions for the cattle herd and sheep flock of an average herder household is presented in Table 1 and Table 2. Overall, a relatively high annual rate (on average, 145 and 143 tCO2e) and per unit live weight of GHG emission (32.3 and 23.1 kgCO2e) were respectively estimated for the traditional cattle and sheep herds. Compared to the current herd structure, the annual rate of GHG emission dropped by 43% for the proposed sheep flock. For the restructured cattle herd, it was almost the same for the across the examined life cycle and herd restructuring scenarios, primarily due to a higher rate of GHG emission and the additional cattle finished in the grass-finished operation compared to the traditional operation.

However, when considering the total live weight of sold livestock (as explained in section 5), the GHG emission rate per unit live weight of both cattle and sheep was remarkably dropped across the examined herd restructuring scenarios (64% and 52%, respectively). In addition, improvement in grazing and pasture management and livestock productivity further reduced the GHG emission rate of the restructured cattle herd and sheep flock, particularly under cow-calf and feedlot-finished operations.

Table 2. GHG emissions from current and alternative sheep flock structure and operation scenarios (Note: The green color indicates GHG removal)

Sheep Flock Management*	Operation*	GHG Emission							
		Total (tCO2e/yr)		Rate (kgCO2e/kg live weight)		Change in Total (tCO2e/yr)		Change in Rate(kgCO2e/kg live weight)	
		Min	Max	Min	Max	Min	Max	Min	Max
Current (100 ewes)	Traditional	118	168	17	25	-	-	-	-
Restructured (100 ewes)	Grass-finished	81	115	11	15	-37	-53	-7	-10

Sheep Flock Management*	Operation*	GHG Emission							
		Total (tCO2e/yr)		Rate (kgCO2e/kg live weight)		Change in Total (tCO2e/yr)		Change in Rate(kgCO2e/kg live weight)	
		Min	Max	Min	Max	Min	Max	Min	Max
	Feedlot-finished	73	104	9	12	-45	-64	-9	-13
Restructured & grazing/pasture improved	Grass-finished	56	106	7	14	-61	-62	-10	-11
	Feedlot-finished	51	98	6	11	-67	-70	-12	-14
Restructured & livestock productivity improved	Grass-finished	63	108	8	14	-55	-60	-9	-11
	Feedlot-finished	51	91	6	11	-67	-77	-12	-14

* More information in sections 4 & 5

The findings of this assessment support life cycle and herd restructuring as an effective GHG mitigation strategy to protect or even promote herders' livelihoods as they potentially end with more livestock production and with a relatively lower direct GHG emission rate (or higher GHG emission efficiency), in particular when improving feeding practices and herd productivity, and promoting appropriate grazing and pasture management practices.

Rotational grazing is considered an effective way to decrease GHG emissions from herding. Currently, livestock herds in the *soum* are left to graze one area of land continuously, resulting in eating the grass down to the ground, disturbing vegetation and soil carbon stores. If herds are rotated between different areas or seasonal pastures, then carbon stored in the vegetation and soil can remain intact or even enhanced, and further emissions from those sources will be halted. Rotational grazing also drops direct GHG emissions from grazing livestock. The improvements of rangeland vegetation will reflect a reduction in livestock energy use and the proportion of fresh grass in livestock diet due to increased quantity and quality of pasture forage, thus reducing GHG emissions associated with feed and livestock grazing activities.

1.3 Potential Carbon Sequestration

The cattle herd and sheep flock restructuring examples (see section 5) indicated that in the short-term (i.e., 3-5 growing seasons), the number of grazing cattle and sheep for an average herder household in the *soum* could potentially drop by 20% (333 to 267 SUs) and 30% (381 to 264 SUs), respectively under favorable climate conditions. Based on the vegetation plot data and state and transition models (explained in section 2), the majority of vegetation communities within the *soum* area have the potential to recover in the short-term through optimized grazing and pasture management. It was, therefore, assumed that improved grazing management through the livestock life cycle and herd restructuring (i.e., more intensive to less intensive grazing pressure) and promoting seasonal pasture rotations will potentially result in the rehabilitation of vegetation in degraded rangeland and, consequently, enhancement of rangeland soil carbon sequestration and GHG mitigation capacity in the short-term.

The overall carbon sequestration potential of improved rangelands was estimated based on the reported carbon sequestration rates for the relevant vegetation types and grazing or pasture management practices. Relevant studies and reports were reviewed to obtain realistic uncertainty ranges (i.e., min and max) of carbon sequestration rates (tC/ha/yr) for both rangeland vegetation and soil. This included carbon sequestration rates for different levels of vegetation degradation (heavily vs. moderately degraded), grazing pressures (i.e., high vs. moderate) and grazing system (i.e., continues vs. rotational) practices (see Table A2 in Appendix).

Reasonable carbon sequestration uncertainty ranges were then assigned to the four main ESGs that characterize dominant vegetation communities and soil types in the *soum* area (Table 16; More information in section 2). The assignment of carbon sequestration uncertainty ranges was done by considering coarse estimates of the current state of vegetation and soil and rough estimates of the distribution and area proportion of seasonal pasture types across different ESGs. Finally, the area of different ESGs was used to estimate the total annual potential carbon sequestration of *soum*'s rangeland under improved grazing and pasture management in average climate conditions.

The estimated potential carbon sequestration of improved soil and vegetation across the *soum*'s rangelands is presented in Table 3. Overall, applying carbon sequestration coefficients to the major ESGs in the *soum* area led to an annual sequestration estimate of 99.8 to 224.3 thousand tons of carbon or 366.1 to 897.1 thousand tons of CO2e from rangeland vegetation and soil, of which 86.8% to 93% originated from carbon sequestration in rangeland soil and the remains from carbon sequestered in improved rangeland vegetation. Accordingly, the corresponding annual sequestration rate across different ESGs was 0.12 to 0.27 tons carbon per hectare per year or 0.44 to 1.07 tons CO2e per hectare per year.

Considering annual conservative GHG emission rates of 1814 and 234 kg CO2e per head of cattle and sheep respectively (see Table A1 in Appendix), the carbon sequestration potential of improved rangeland can annually mitigate direct GHG emissions from 202 to 495 thousand cattle heads or 1,570 to 3800 thousand sheep heads. Also, considering an annual conservative carbon removal of 20 kg from the air through photosynthesis by a typical young tree, the carbon removal potential of improved rangeland can annually be equal to carbon removal by 18.3 to 44.8 thousand trees.

Table 3. Potential carbon (C) sequestration of different ecological site groups under improved grazing and pasture managements

Ecological Site (ESGs)*	Area (10^3 ha)	Vegetation C Sequestration				Soil C Sequestration			
		Total C (10^3t/yr)**		Total CO2e (10^3t/yr)!		Total C (10^3t/yr)		Total CO2e (10^3t/yr)	
		Min	Max	Min	Max	Min	Max	Min	Max
6. *Stipa Krylovii*-Small bunch grass-Forbs dry steppe rangeland	302.0	5.7	6.8	20.9	24.8	45.3	102.7	166.1	442.9

Ecological Site (ESGs)*	Area (10^3 ha)	Vegetation C Sequestration				Soil C Sequestration			
		Total C (10^3t/yr)**		Total CO2e (10^3t/yr)!		Total C (10^3t/yr)		Total CO2e (10^3t/yr)	
		Min	Max	Min	Max	Min	Max	Min	Max
9. *Stipa grandis-Elymus chinensis-*Forbs dry steppe rangeland	275.7	4.3	5.1	15.9	18.8	13.8	41.4	50.5	151.6
7. *Stipa krylovii*-grass dry steppe rangeland	192.2	2.8	3.3	10.3	11.9	19.2	48.0	70.5	176.1
10. *Achnatherum splendens* rangeland	55.8	0.3	0.4	1.2	1.4	8.4	16.7	30.7	69.5
Total	**835.7**	**13.2**	**15.5**	**48.3**	**56.9**	**86.7**	**208.8**	**317.8**	**840.2**

* More information in section 2; Fig. 1 & Table 1.

** Carbon sequestration rates across ESGs ranged from 0.006 to 0.022 and 0.05 to 0.34 tC/ha/yr for vegetation and soil, respectively (see Table A2 in Appendix).

! A conversion factor of 44/12 or 3.67 was used to calculate the CO2e of the carbon sequestration estimates.

1.4 GHG Emission and Removal Impact

The analysis of the historic livestock population statistics indicated an overall increase of 57% in livestock population size between 2017 and 2021 (Table 4). Considering this historical rate of change, by 2025, the total livestock population in the *soum* can be potentially increased by 143 thousand heads of livestock, which translates to an estimated total of 91.8 thousand tons of extra CO2e emissions from the livestock sector. While, taking livestock population measures such as restructuring cattle herds and sheep flocks and, for example, preventing further increases in the populations of other livestock types (in particular, horses and goats) can lead to a projected livestock population size between the 2017 and 2021 levels. In other words, if appropriate measures are taken to prevent and remove additional livestock heads from the region, by 2025, a total of 113 thousand tons of extra direct CO2e emissions can potentially be removed from the livestock sector, and the overall GHG emission of the sector can potentially decrease to a level below the 2021 level (Table 4).

Table 4. Historical and projected livestock population and GHG emission (Note: The green color indicates GHG removal or no emission and the red mean additional GHG emissions)

Description	Scenario	Year	Livestock Types					
			Horse	Cattle	Camel	Sheep	Goat	Total
Livestock Population (10^3 heads)	Historic	2017	25.1	17.6	0.7	70.1	45.6	159.0
		2021	38.4	30.9	0.9	109.8	69.5	249.6
	Change (%)	2017-2021	53.2	76.1	36.8	56.7	52.4	57.0
	Projected	2025	58.8	54.4	1.3	172.1	106.0	392.6
	Optimized*	2025	38.4	24.7	0.9	76.9	69.5	210.5
GHG intensity (tCO_2e/head/yr)!			0.91	2.06	1.61	0.26	0.23	-
GHG emission (10^3tCO_2e/yr)	Historic	2017	22.7	36.2	1.1	17.9	10.4	88.3
		2021	34.8	63.8	1.5	28.0	15.9	143.9

Description	Scenario	Year	Livestock Types					
			Horse	Cattle	Camel	Sheep	Goat	Total
	Projected	2025	53.3	112.4	2.1	43.9	24.2	235.7
	Optimized	2025	34.8	51.1	1.5	19.6	15.9	122.8
GHG emission change ($10^3 tCO_2e/yr$)	Historic	2017-2021	12.1	27.6	0.4	10.1	5.5	55.6
	Projected	2021-2025	18.5	48.6	0.6	15.9	8.3	91.8
	Historic - Optimized	2021-2025	0.0	-12.8	0.0	-8.4	0.0	-21.2
	Projected - Optimized	2025-2025	-18.5	-61.3	-0.6	-24.3	-8.3	-113.0

* Based on 20% and 30% reductions for cattle and sheep populations, respectively, due to herd restructuring. For other livestock types, the population was kept at the same size as in 2021.
! Values are based on Shi et al., 2022 (Front. Public Health, 11).

These simple estimates of GHG projections for the year 2025 are based on coarse GHG emission intensities for different livestock types and by considering assumptions like no improvement in livestock productivity and management and no major climate event or market condition that drastically alter livestock number in the *soum*. However, when you put these estimates of direct annual GHG emissions in 2025 together with the annual potential carbon sequestration from rangeland, if no adaptive measures are taken to prevent and remove additional livestock from the landscape and rehabilitate soil and vegetation of degraded rangelands in the *soum*, then in the year 2025 alone, an estimated total GHG emission removal opportunity of 479 to 1010 thousand tons of CO2e from the *soum*'s livestock sector will be missed. This would roughly equal annual carbon removal by 23.9 to 50.5 thousand trees (i.e., 20 kg CO2e/yr removal by a single young tree).

These figures demonstrate the large mitigation potential of GHG emissions from the livestock sector, particularly through carbon sequestration in vast rangeland areas of the *soum* and the country. It also demonstrates the importance of developing effective climate-resilient pasture management measures and policies that, while sustaining herders' livelihoods under a changing climate, promote the provision of undervalued environmental goods and services from rangelands (see Section 6), including their carbon sequestration and GHG mitigation capacity. Local herders must play a fundamental role in the development process of new policies, as they deeply understand their surrounding landscapes and the environmental good and services essential to their herding livelihood systems.

1.5 Conclusions and Limitations

This preliminary assessment demonstrates the potential GHG emission and removal from the traditional livestock sector in the Bayantumen Soum. It demonstrates how restructuring the existing livestock herds and improvement in grazing and livestock management can potentially increase the GHG emission efficiency of livestock products (i.e., lower CO2e intensity per unit of live weight) while increasing the total production of livestock live weight for an average herder household. Even more remarkably, it demonstrates the considerable opportunity for GHG removal and mitigation through carbon sequestration in the degraded rangeland soil and vegetation that can potentially be restored through improved livestock and grazing practices, as explained in section 8.

Efforts to address livestock related GHG emission risks are likely to require systemic changes in Mongolian livestock management and marketing to sustain herders' incomes over the long term. Community-based rangeland monitoring and management can support local agreement on livestock mobility or seasonal pasture rotation, an adaptive strategy traditionally used by Mongolian herders to prepare for and respond to pasture and climatic conditions. In addition, adaptive measures that reduce livestock mortality and increase livestock productivity are required to minimize the herders' only offset mechanism or increasing their herd size to compensate for possible livestock losses from harsh climate seasons (i.e., like dzud).

Establishing feedlots for mixed livestock production systems (i.e., feedlot-finished) requires further assessment. On the one hand, feedlots get grazing livestock off the pasture, thus contributing to grazing pressure adjustment while raising more livestock in a shorter period and lowering GHG emissions per kg of livestock product compared to grass-finished production systems. On the other hand, feedlots in mixed systems require special diet composition in different stages (e.g., high fibrous ingredients in the growing stage and high-energy grains during the finishing stage). This can potentially lead to increased CO2e emissions related to feed production, processing and transport. Therefore, decision-making should pay much attention to the source and type of feed that will be fed to the livestock. In addition, the concentration of livestock over small areas can lead to challenges in manure management and, eventually, higher GHG emissions and water pollution issues. Legumes as protein-rich and nutritious feed for the livestock can enrich soils with nitrogen, increase forage production, and promote carbon sequestration at a rate that, in some cases, is less achievable through other practices in cultivated lands. Using legume species for livestock feed and fodder production and promoting them in rangeland vegetation composition can be an adaptive measure for mitigating GHG emissions and climate change impacts.

Reports about GHG emissions and carbon sequestration rates are particularly rare for Mongolia. While great care has been taken to ensure that the input data and the results were of the highest quality possible, there remain several limitations in the underlying datasets and therefore projected changes. These results provide a basis for identifying adaptation pasture and livestock management measures that target the mitigation of GHG emissions from the livestock sector. However, they also suggest that more effort needs to be put into a systematic assessment of the sector's potential GHG emissions and removal. This includes considering the IPCC Guidelines Tier 3 methods that require locally appropriate emission factors for different livestock types and practices that can be obtained though direct measurement of GHG emissions from different aspects and stages of the livestock life cycle.

Table A1: Reported emission intensity factors for cattle and sheep under different grazing management and production practices.

Location	Cattle						Sheep						Reference	Remarks
	Baseline		Pasture		Livestock		Baseline		Pasture		Livestock			
	(kg CO2e /kg LW)	(kg CO2e/head)	(kg CO2e /kg LW)	(kg CO2e/head)	(kg CO2e /kg LW)	(kg CO2e /head)	(kg CO2e /kg LW)	(kg CO2e/head)	(kg CO2e /kg LW)	(kg CO2e/head)	(kg CO2e /kg LW)	(kg CO2e /head)		
Mongolia	10.8		9.9				15.4		13.1				Asian Development Bank, 2013 (Publication Stock No. RPT136010)	
Argentina	19.6		13.7		17.8								Nieto et al., Sustainability 2018 (10)	Rotational vs Continuous grazing
Scotland								210			163		Moxey & Thomson, 2021, Scottish Government (Sheep Emission Report)	
India							9.5	350						
Mediterranean													Ripoll-Bosch et al., 2013, Agric. Syst. (116)	Zero grazing and pasture grazing : 19.5 and 25.9 kg CO2e per kg of LW
New eland	6.9	####					17	300					Carbon Farming Group, 2021; https://www.carbonfarming.org.nz/	
China													Tang et al., 2019, Science of the Total Environment (654)	methane emission decrease up to 50 % from HG to MG
Western Canada	10.4						13.2						Dyer and Desjardins, 2014, Sustainable Agriculture Research (19)	
Western Australia							8.2				7.7		Black et al. 2021, Animals (11)	livestock productivity improvement of 10% results in 6.5 % decrease in emission.

Table A1 continued

Location	Cattle						Sheep						Reference	Remarks
	Baseline		Pasture		Livestock		Baseline		Pasture		Livestock			
	(kg CO_2e/kg LW)	(kg CO_2e/head)	(kg CO_2e/kg LW)	(kg CO_2e/head)	(kg CO_2e/kg LW)	(kg CO_2e/head)	(kg CO_2e/kg LW)	(kg CO_2e/head)	(kg CO_2e/kg LW)	(kg CO_2e/head)	(kg CO_2e/kg LW)	(kg CO_2e/head)		
Mongolia	10.8		9.9				15.4		13.1				Asian Development Bank, 2013 (Publication Stock No. RPT136010)	
Argentina	19.6		13.7		17.8								Nieto et al., Sustainability 2018 (10)	Rotational vs Continuous grazing
Scotland								210			163		Moxey & Thomson, 2021, Scottish Government (Sheep Emission Report)	
India							9.5	350						
Mediterranean													Ripoll-Bosch et al., 2013, Agric. Syst. (116)	Zero grazing and pasture grazing : 19.5 and 25.9 kg CO_2e per kg of LW
New eland	6.9	####					17	300					Carbon Farming Group, 2021; https://www.carbonfarming.org.nz/	
China													Tang et al., 2019, Science of the Total Environment (654)	methane emission decrease up to 50 % from HG to MG
Western Canada	10.4						13.2						Dyer and Desjardins, 2014, Sustainable Agriculture Research (19)	
Western Australia							8.2				7.7		Black et al. 2021, Animals (11)	livestock productivity improvement of 10% results in 6.5 % decrease in emission.

Table A2: Reported carbon sequestration rates under different grazing management and production practices.

Vegetation Type	Soil depth (cm)	SOC (tC/ ha)	Baseline		Pasture/ grazing		Reference	Remarks
			Rate (tC/ha/yr)	Rate (t CO2e/ ha/yr)	Rate (t SOC/ha /yr)	Rate (t CO2e/ha/yr)		
Downstream wetland	0-100	65.0					Liu et al., 2022; Ecological Indicators 139 (2022) 108945	
Semi-arid grassland					0.10	0.35	Asian Development Bank, 2013 (Project No. 47286-001)	
Semi-arid grassland					0.03	0.12	Asian Development Bank, 2013 (Publication Stock No. RPT136010)	Improved grassland management; Conservatively assumed no soil carbon emission in baseline
Semi-arid grassland							Byrnes et al. 2018, J. Environ. Qual.(47)	Heavy grazing decrease soc by 14%
Semi-arid grassland							Byrnes et al. 2018, J. Environ. Qual.(47)	Rotational vs. contineous grazing increase soc by 29%
Mountain steppe - heavily degraded	0-20		0.26	0.95			Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Mountain steppe - heavily degraded	0-20	10.9					Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Mountain steppe - lightly degraded	0-20		0.30	1.10			Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Mountain steppe - moderately degraded	0-20	31.0					Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Mountain steppe - moderately degraded	0-20		0.35	1.28			Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Riparian meadow - heavily degradated	0-20	17.0					Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
Riparian meadow - moderately degraded	0-20	34.5					Chang et al. 2015, Agriculture, Ecosystem and Environment (212)	
semi-arid grasslands					0.05	0.18	Conant and Paustian, 2017, Ecological Applications (11)	Change from overgrazed to moderately grazed
Meadow steppe	0-20	66.5					Dai et al. 2014	
Typical steppe	0-20	34.1					Dai et al. 2014	
Grassland							Eze et al., 2018, J. Environ. Manage.(223)	Heavy grazing decrease soc by 27%
Grassland							Eze et al., 2018, J. Environ. Manage.(223)	Sowing legumes increase soc by .4 to .9 ton/ha/yr
Grassland			0.27	0.99			Fan et al., 2012, Grassland and Turf (32)	
Typical steppe	0-30	22.7					Feng et al. 2019	
grassland			0.49	1.80	0.39	1.80	Garnett et al., 2017, University of Oxford	Review of literature

Table A2 Continued

Vegetation Type	Soil depth (cm)	SOC (tC/ha)	Baseline Rate (tC/ha/yr)	Baseline Rate (t CO2e/ha/yr)	Pasture/ grazing Rate (t SOC/ha/yr)	Pasture/ grazing Rate (t CO2e/ha/yr)	Reference	Remarks
rangeland					0.06	0.23	Henderson et al. 2015, Agriculture, Ecosystem and Environment (207)	Change in grazing pressure; Conservatively assumed no soil carbon emission in baseline
rangeland					0.55	2.00	Henderson et al. 2015, Agriculture, Ecosystem and Environment (207)	Legume sowing add 2 t/co2/ha/yr (compensation for nitrous oxide emission); Conservatively assumed no soil carbon emission in baseline
Semi-arid grassland					0.15	0.55	Henry et al., 2015	Due to vegetation recovery/ improvement; Conservatively assumed no soil carbon emission in baseline
Semi-arid grasslands					0.10	0.36	Lal, R., 2004, Geoderma (123)	Improved grazing practices; Conservatively assumed no soil carbon emission in baseline
Semi-arid grasslands					0.20	0.73	personal communication	
Semi-arid grasslands							Sagar et al. 2019 Journal of Plant Ecology (12)	Conversion of biomass to carbon - 41% for Stipa species
Mountain steppe		26.6					Upton et al., 2015, Plan Vivo Project Design Document	
Mountain steppe					0.03	0.10	Upton et al., 2015, Plan Vivo Project Design Document	Grazing pressure from 80 to 50%
Mountain steppe - summer					0.08	0.12	Upton et al., 2015, Plan Vivo Project Design Document	Grazing pressure from 80 to 50%
Mountain steppe - winter					0.08	0.28	Upton et al., 2015, Plan Vivo Project Design Document	Grazing pressure from 80 to 50%
Riparian meadow		31.7					Upton et al., 2015, Plan Vivo Project Design Document	
Riparian meadow - summer					0.10	0.36	Upton et al., 2015, Plan Vivo Project Design Document	Grazing pressure from 80 to 50%
Riparian meadow -winter					0.05	0.02	Upton et al., 2015, Plan Vivo Project Design Document	Grazing pressure from 80 to 50%
Mountain steppe -Moderately degraded	0-20	33.2					Wang et al., 2013	
Mountain steppe -haveliy degraded	0-20	11.8					Wang et al., 2013	
Riparian meadow - Moderately degraded	0-20	24.1					Wang et al., 2013	
Riparian meadow -haveliy degraded	0-20	16.3					Wang et al., 2013	
Mountain steppe -Moderately degraded	0-20				0.21	0.77	Wang et al., 2013	Between 0.13～ 0.65 t C ha-1yr-1 for degraded pastures under changed grazing (summer grazing)
Mountain steppe -haveliy degraded	0-20				0.34	1.25	Wang et al., 2013	Between 0.13～ 0.65 t C ha-1yr-1 for degraded pastures under changed grazing (summer grazing)
Riparian meadow - Moderately degraded	0-20				0.22	0.81	Wang et al., 2013	Between 0.13～ 0.65 t C ha-1yr-1 for degraded pastures under changed grazing (summer grazing)
Riparian meadow -haveliy degraded	0-20				0.28	1.03	Wang et al., 2013	Between 0.13～ 0.65 t C ha-1yr-1 for degraded pastures under changed grazing (summer grazing)
Typical steppe	0-100	67.0					Yang et al. 2007	
Typical steppe							Zhou et al. 2017, Glob. Chang. Biol.(23)	Heavy grazing decrease soc by 10%