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Climate-smart legume-grass system can reduce greenhouse gas emissions and net SOC

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Abstract: Improving forage productivity with lower greenhouse gas (GHG) emissions from limited grassland has been a hotspot of interest in global agricultural production. In this study, we analysed the effects of native grass species (*Artemisia capillaris* L.; *Lespedeza daurica* L. & *Stipa bungeana* L.), with legumes (alfalfa; M-vetch & Pea-shrub), and native grasses+legumes mistures (*artemisia capillaris* + alfalfa; *Lespedeza daurica* + pea shrub; and M-vetch + *Stipa bungeana*) overseeded mixtures were tested to quantify on GHG emissions, net soil organic carbon potential (Net SOC). Fodder forage yield-based greenhouse gas intensity (GHGI), soil chemical properties and forage quality and productivity in Typical Steppe grassland in Gansu province of China during the cropping season on 2023 and 2024. The research results demonstrated that high seeded intensity alfalfa + native grass significantly improved forage production. The maximum total dry matter yield (DMY) during 2023 and 2024 was attained from legumes+native grass at optimum seeding (9,317 and 10,461 kg ha^{-1}), and legumes mixtures vs native grass mixtures (8,513 and 9,892 kg ha^{-1}) at higher seeding rates. The yearly collective GHG emissions from legume + native grass mixtures were lower than alfalfa sole-culture. Alfalfa with native grass mixtures significantly reduced greenhouse gas intensity (GHGI) compared with the native grasses and sole alfalfa planting system. Moreover, experiment outcomes showed that native grass, alfalfa and alfalfa- native grass mixtures differentially affected on chemical properties of soil. Lower soil pH and C/N ratio were documented in higher planting density of alfalfa when grown under sole system, whereas legumes and native grasses mixtures significantly (17%) increased soil organic carbon (SOC) and soil total nitrogen (STN) contents up to 11.2% respectively. Notably, alfalfa maximum planting density with native grasses combinations are essential for improving fodder/forage quality, productivity by mitigating the GHG emissions from the highly-productive agroecosystems. In conclusion, the Legumes+Native grass mixture enhanced Net-SOC and GHGI in Typical Steppe grassland systems, whereas restoring soil nitrogen and ecosystem functioning with high quality forage yield. These climate-smart agricultural practices could contribute to the development of sustainable grassland production in China under extreme weather conditions by investing minimum input resources.

1. Introduction: The Chinese grasslands ecosystem is greatly affected by climate change and human activity via land use and cover change, direct grazing, mowing, infrastructure and recent development. Grasslands of China are vast (approximately 400 Mha), and some 90% are overgrazed and considered degraded, although only 10%

have become so badly degraded and decertified (Kemp**,** 2019). One of the key challenges is degradation of grasslands in China as about 40% of all agricultural and natural land is occupied by rangelands (Ge et al.**,** 2022; Chang et al.**,** 2024). These grasslands have gone through severe degradation over time under extensive anthropological disturbance and drastic climate change (Arshad et al., 2020; Zhang et al.**,** 2022). Among the complex causes of grassland degradation, overgrazing is considered a major driver (Maestre et al., 2022) leads to poor soil fertility. The growing demand on ruminant-sourced food gives pressure on the natural ecosystems, including the Typical Steppe agroecosystem in Gansu province. Moreover, degradation of rangelands proceeds at a rate of 2 Mha yr^{-1} which is equivalent to an annual loss of 1.5% of the grassland biome area in China. In China, nearly 61% of grasslands suffer from degradation due to intensive grazing (Hou et al., 2021). Degraded grasslands not only fail to provide subsistence for the local people (Zhao et al.**,** 2017; Bardgett et al.**,** 2021), but also fail to mitigate climate change, negative impact on greenhouse gas emissions (GHG) and C-stocks (Wang et al.**,** 2016; Deng and Shangguan, 2021).

Grasslands are among the most important terrestrial carbon pools in China, storing approximately 3.06 Pg of vegetation carbon and 41.03 Pg of soil carbon (Ni 2002). Degradation intensity significantly affects below-ground C and N cycling in grasslands system. Heavy grazing decreases soil C and N pool sizes which critically important ecological and economic values while from various degrees of biodiversity degradation in China (Hou et al.**,** 2021), and left with zero seed bank and facing feed shortage, soil erosion in coming future. Previous studies indicate that pre-season climatic elements such as temperature, precipitation, sunshine and thermal conditions play a dominant role in influencing the phenological period (Gastaldi et al., 2020). For example, increasing precipitation can extend the growing season in Canadian and Ethiopian grasslands, and precipitation in the previous autumn and winter have led to an earlier vegetation SOC in the Tibetan Plateau (Workie and Debella, 2018). Grasslands are sensitive to climate change, and the carbon sequestration ability is closely related to water availability. Increasing temperature followed by prolong-droughts is impacting on different growth stages, thereby reducing the fertility input from grasses to soil (Derner et al. 2006; Zuo et al. 2018). Multiple studies worldwide reported the optimization of seeding rates with changing environmental condition is essential (Li-li et al. 2019; Workie and Debella, 2018) to recover the grasslands productivity, nutritional values of herbage in parallel richness of soil fertility. There is dire need to test combination climate-smart grassland management practices such as high planting density of perennial native grasslands and multiple legumes species. Introduction to conservative agroecosystem including year-around soil mulching followed by no-tillage to reduced emission. Our research aims those changes in land-use management might positively impact on yield and agroecosystem. The key scientific problems to be solved under long-term field experiment: a) How does the area-specific planting density of legume grasses vs native grasses to impact forage productivity, quality and SOC? b) Also quantify the response of grasslands under native + legumes system to current climate variations and ecosystem services? c) Best climate-smart grasslands practices adaptive to the local environmental conditions to promote forage productivity by canceling greenhouse gases emissions?

2.Methods

2.1. Study site: The research area is located in the Huanxian county and typical steppe grassland/agricultural trial station in Gansu province, China (37.12°N, 106.84°E, 1700 m a.s.l), which is the largest inter and intra-annual precipitation variability in the world (Huang et al., 2022). The mean annual temperature is 7.8 °C and the mean annual precipitation is 289.8 mm, occurring mainly (>70%) from April to September (the growing season). The typical soil type is classified as loessal soils with sand texture.

2.2. Experimental design: The field experiment will be carried out in a typical steppe (slope≈5°) with combination of multis-legume species composition and soil conditions under the randomized complete block design (RCBD) followed by No-tillage (mentioned in schematic I & II). The project interventions will be carried out in Huanxian Grassland areas of Gansu Province by integration of three legume grasses Alfalfa (*Medicago sativa* L.); Milkvetch (*Astragalus laxmannii* L.); Pea-shrub (*Caragana korshinskii* L.) of optimum, high, very high seeding rates (15, 20 & 25 kg ha-1); followed by zero-tillage.

2.3. Compute soil organic carbon (SOC): Methods include Walkley and Black and Photometric methods, while dry combustion includes ignition tests (SoilOptix®). Walkley and Black Method relies on the oxidation of potassium dichromate ($K_2Cr_2O_7$) that is acid catalyzed as shown in Fig. 1. The heat from the dilution raises the temperature to induce substantial oxidation of carbon-to-carbon dioxide. A modified Walkey and Black Method called Meibus uses the same procedure but includes sulphuric acid with $K_2Cr_2O_7$ (Usman, et al., 2022). Also applied the IPCC Tier > 1 methodology assumes that the SOC in a specific situation is given by:

$$SOC = SOCREF * FLU * FMG * FI$$

where SOCREF is the SOC under native vegetation (assumed to be native grass species), and FLU, FMG and FI are factors dependent on land use by legume crops species, management practices and inputs material.

Figure 1. A graphic representation of the different SOC stock baselines and the associated changes that were sampled and measured under the legumes + native grass species seeding proportion% (optimum>high) production systems.

3. Results & discussions

3.1. Agrometeorology and SOC at a landscape scale: Pastures are particularly important to the global carbon cycle because of their size and relatively high SOC reserves as compared to equivalent croplands in temperate climates. Large portions of the world's grasslands are under intense environmental pressure as a result of deterioration caused by overgrazing, which could affect SOC stocks. At the landscape scale, however, changes in SOC stocks are caused by complicated interactions between various variables, including climate, land management, and inherent soil biophysical characteristics, such as soil texture and/or chemical qualities. The connection between precipitation (mm) and soil organic carbon (g C m^{-2}) at a landscape measurement level. Thus, to quantify management effects on SOC stocks from 2001 to 2022 we compared the effects of abiotic site conditions, long-term plot experiments showed that areas with higher annual rainfall (>300 mm) exhibited greater SOC levels compared to regions with lower precipitation levels (<250 mm). Moreover, at a landscape scale, SOC content was positively correlated (>22.5%) with the amount and distribution of rainfall (> 300mm). Areas experiencing more consistent and higher rainfall showed higher SOC concentrations above 2214 g C m^{-2}) in the topsoil layers from 20-30cm soil pool. Long-term data analysis discovered a significant positive connection among yearly rainfall changeability (250-300mm) and SOC accumulation (~17.3-21.5%) mentioned in table 1, demonstrating the role of rainfall patterns in shaping SOC dynamics over time.

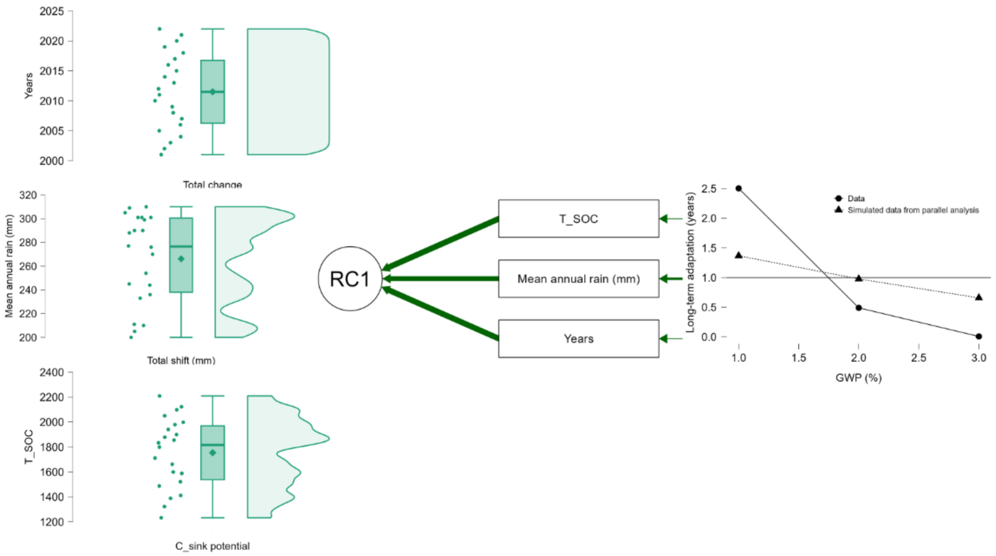


Figure 2. Yearly contribution mechanism determination on the bases of observed field data (RC1) total SOC, rainfall and mean annual shift (mm) at typical steppe, Gansu province of China.

3.2. Legumes vs. native grass species in typical steppe:

When legumes grass species grown with native grasses at optimum seeding (O.S) and high seeding (H.S) rates plots found to significantly ($P < 0.05$) reduced ST (soil temperature) by 3.72% and 5.71%, soil pH by 1.37% and 2.18%, and C:NC/N ratio by 10.03% and 11.18% shown in Fig. 2. Equally, improved SM (soil moisture) content (%) by 2.81% and 3.61%, SOC (soil organic carbon) up-to 2.96% and 3.56%, and soil total nitrogen (STN) by 12.58% and 17.37%, linked to native grass and legumes species sole-cultures in 2024, respectively. Furthermore, winter-cuttings increased soil temperature (2.24% and 2.38%) and CO_2 in Fig. 3, while decreased soil moisture (1.18% and 1.47%) compared to spring-cuttings. Additionally, the initial results indicated that legumes overseed (O.S) with native grasses significantly ($P < 0.05$) increased the forage yield by 51.48% and 39.65%, crude protein (CP) content by 19.86% and 24.13%, ash content by 12.45% and 26.89%, and relative feed values (RFV) by 4.78% and 7.13%.

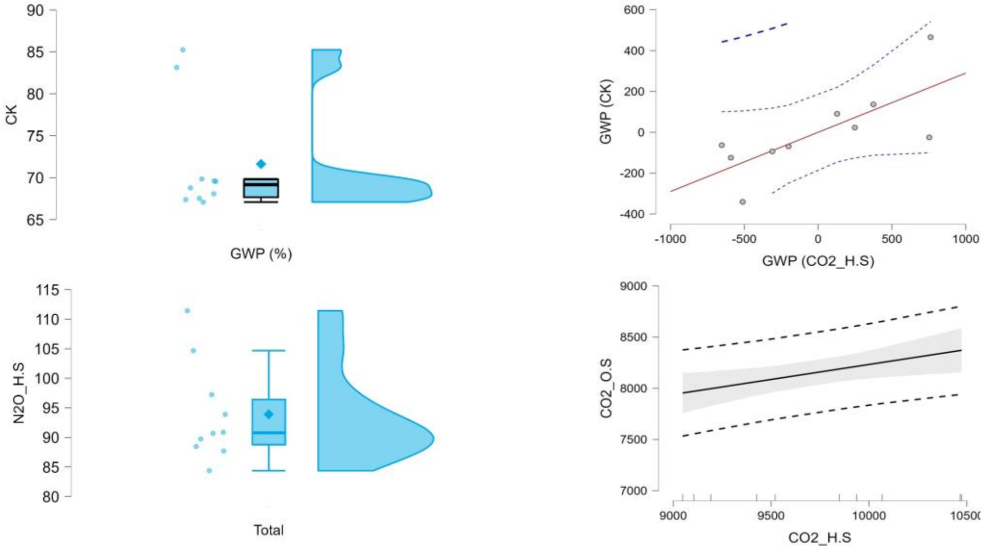


Figure. 3. Accumulated contribution of legume + native grass species production for quality and yield to GHG global warming potential of typical stepper of Gansu province in China.

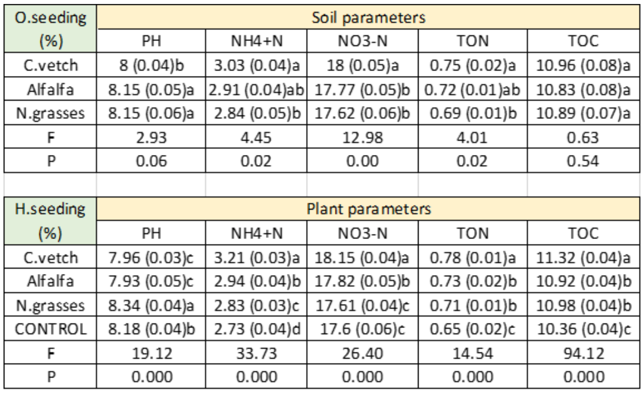
Cultivating forage crops is crucial to improve feed quality, production, and grazing is an important utilisation method to improve SOC. Improving soil organic carbon (SOC) content and reducing carbon dioxide (CO_2) emission through planting legumes species at different planting proportions with existing native grass species. Soil is the major carbon pool of grassland ecology and stores 26–36% of the carbon in the terrestrial ecosystem (Zhang et al. 2018; Pourshirazi et al. 2022).

4. Conclusion

The increase of storage or SOC sequestration of content is significant to improve crop productivity and soil fertility as well. Conceivable trends in soil organic carbon (SOC) stocks in agroecosystem sequestration scenarios and subsequent implementation of soil carbon sequestration trials. (i) Soil organic carbon (SOC) shares are assumed to be in steady pool/conversion with zero-change in changing climate scenario, (ii) SOC stocks are projected to increase even without C-sequestration measures in the warming potential-as-usual scenario, (iii) Stocks of SOC are expected to decline in the SOC despite the implementation of C-sequestration actions, and (iv) SOC stocks are expected to decline if no C-sequestration measures are implemented under legumes planting proportions.

5. Supplementary material:

Table 1. Parametrization of soil properties under legume + native grass species at optimum seeding and high seeding rates in typical steppe growing system of Gansu province, China.



O.seeding (%)	Soil parameters				
	PH	NH4+N	NO3-N	TON	TOC
C.vetch	8 (0.04)b	3.03 (0.04)a	18 (0.05)a	0.75 (0.02)a	10.96 (0.08)a
Alfalfa	8.15 (0.05)a	2.91 (0.04)ab	17.77 (0.05)b	0.72 (0.01)ab	10.83 (0.08)a
N.grasses	8.15 (0.06)a	2.84 (0.05)b	17.62 (0.06)b	0.69 (0.01)b	10.89 (0.07)a
F	2.93	4.45	12.98	4.01	0.63
P	0.06	0.02	0.00	0.02	0.54

H.seeding (%)	Plant parameters				
	PH	NH4+N	NO3-N	TON	TOC
C.vetch	7.96 (0.03)c	3.21 (0.03)a	18.15 (0.04)a	0.78 (0.01)a	11.32 (0.04)a
Alfalfa	7.93 (0.05)c	2.94 (0.04)b	17.82 (0.05)b	0.73 (0.02)b	10.92 (0.04)b
N.grasses	8.34 (0.04)a	2.83 (0.03)c	17.61 (0.04)c	0.71 (0.01)b	10.98 (0.04)b
CONTROL	8.18 (0.04)b	2.73 (0.04)d	17.6 (0.06)c	0.65 (0.02)c	10.36 (0.04)c
F	19.12	33.73	26.40	14.54	94.12
P	0.000	0.000	0.000	0.000	0.000

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