Market Costs and Financing Options for Grassland Carbon Sequestration: Empirical and Modelling Evidence From Qinghai, China

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Asia's grasslands provide livelihoods for some of the region's poorest people. Widespread grassland degradation reduces the resilience and returns to herding livelihoods. Reversing degradation and conserving grasslands could not only improve herders' situation, but also make a huge contribution to mitigating climate change by sequestering carbon in soils. However, the means for reaching each of these objectives are not necessarily the same. To realize this potentially huge dual livelihood/climate change mitigation outcome from improved grassland management, it is necessary to have detailed understanding of the processes involved in securing better livelihoods and sequestering carbon. Based on household surveys on the Tibetan Plateau and modeling results, this study estimates economic and market costs of grassland carbon sequestration, and analyzes the implications of household and carbon project cash flows for the design of financing options. Five scenarios are modeled involving cultivation of grass on severely degraded grassland (all scenarios) and reduced grazing intensity on less degraded land, which requires destocking by 29, 38, 47, 56, and 65% in each scenario). Modeling results suggest that economic benefits for herders are positive at low levels of destocking, and negative at high levels of destocking, but initial investments and opportunity costs are significant barriers to adoption for households in all destocking scenarios. Existing rural finance products are not suitable for herders to finance the necessary investments. Market costs–the cost at which transactions between herders and carbon project developers are feasible–depend on the scale of project implementation but are high compared to recent carbon market prices. Large initial investments increase project developers' financing costs and risk, so co-financing of initial investments by government would be necessary. Therefore, public policies to support grassland carbon sequestration should consider the potential roles of a range of financial instruments.

Keywords: grassland, soil carbon (C) sequestration, carbon offsets, investment cost, opportunity cost, China

INTRODUCTION

The Paris Agreement aims to limit the rise in global average temperatures to below 2°C by 2100 and increase adaptation to adverse effects of climate change in a manner that does not threaten food production (UNFCCC 2015). Soil carbon sequestration in agricultural lands has been identified as having a crucial role in meeting the Paris Agreement's objectives, since feasible measures to mitigate non-CO_2 agricultural emissions are insufficient to achieve the 2°C limit, and soil carbon sequestration is a co-benefit of many nature-based adaptation measures (Wollenberg et al., 2016; Bossio et al., 2020). Smith et al. (2007) estimated that grazing land management has the second largest technical mitigation potential in the agriculture sector at >1300 million metric tons of carbon dioxide equivalent (tCO_2e) per year, most of which is attributed to soil carbon sequestration. Improving management of the world's grasslands could lead to major improvements in the livelihoods of some of the world's poorest peoples as well as a significant contribution to climate change mitigation by sequestering carbon. However, the means and priorities for grassland management are not necessarily the same when pursuing each of these two objectives. To realize this potentially huge dual livelihood/climate change mitigation outcome from improved grassland management, it is necessary to have detailed understanding of the processes involved in securing better livelihoods and sequestering carbon.

Grassland soil carbon sequestration has received considerable attention amongst Asian climate policy makers. Of 46 Asian countries that submitted an initial Nationally Determined Contribution under the Paris Agreement, 36 included agriculture in the scope of either adaptation or mitigation commitments, and 15 explicitly mentioned measures related to soils, grassland or livestock (Richards et al., 2016). Despite the broad policy relevance of grassland soil carbon sequestration, there has been limited progress in designing and implementing policy measures with positive effects on soil carbon in many countries. Within Asia, China is one notable exception, where large potential effects on grassland soil carbon stocks have been estimated in response to government funded programs to restore degraded grasslands (Wang et al., 2011; Deng et al., 2017). However, while improvements in grassland conditions have been achieved, several studies have suggested low levels of compliance with stocking rate limits and/or adverse impacts on herders' net incomes, largely due to increased production costs (e.g., Yin et al., 2019; Zhang et al., 2019). Thus, there is interest in the potential of augmenting incentive schemes by explicitly accounting for the mitigation externalities generated, and linking herders to China's nascent carbon market (Wang and Wilkes 2014). China's forestry sector has actively engaged in carbon markets in the past decade (Zhou et al., 2017). However, no carbon offsets from grazing management have been transacted, despite the approval of a grassland management GHG accounting methodology by the relevant Chinese government agency in 2014 (NDRC 2014). In other Asian countries, national emissions trading schemes (e.g., in Kazakhstan) and international market or non-market

mechanisms under negotiation in relation to Article 6 of the Paris Agreement may also be potential sources of finance for grassland carbon sequestration (Edmonds et al., 2019). Therefore, it is relevant for grassland management in both China and the wider Asian region to better understand the economics and financing needs of grassland carbon sequestration in a carbon market context.

China's publicly funded incentive programs have been the topic of considerable research. There is a large body of literature on the biophysical impacts of measures promoted in these programs, including carbon sequestration (e.g., Xiong et al., 2016; Hao et al., 2019; Zhan et al., 2020). In terms of socio-economic impacts, econometric methods have been used to assess the ex post impacts of these programs and provide insights into herders' behavioral responses to incentives (e.g., Hu et al., 2019; Qiu et al., 2020). More recently, bioeconomic modeling has been combined with choice modeling to enable ex ante assessment of herders' likely responses to different policies and combinations of policy measures (Li and Bennett 2019; Behrendt et al., 2020; Brown et al., 2021). However, the existing analysis has not considered the effects of herders' decision-making on grassland soil carbon sequestration. Furthermore, while some research has assessed the transaction costs of implementing public policies for sustainable grazing management (Addison et al., 2020), the transaction costs of providing incentives through carbon market mechanisms have not previously been assessed. This limits understanding of the potential relevance of carbon market mechanisms in Asia's grasslands because market-based carbon projects may only be feasible when both the economic cost of changing herders' management practices is compensated by incentive payments and the cost borne by carbon project developers is below the price they receive for the carbon credits generated (Cacho et al., 2013).

The aim of this paper is to provide a detailed understanding of these issues for a grassland system located in Qinghai Province on the Tibetan Plateau in China. The analysis presented is based on a unique data set on the livestock and grassland management operations of 271 households, coupled with a land resources survey and the results of carbon modeling using Century 4.5 validated for the study site. Bioeconomic modeling is used to assess the response of herders' animal husbandry incomes and soil carbon sequestration to different grassland and livestock management scenarios, and a financial model is used to assess the feasible conditions for carbon project development. The study investigated the following questions: (1) what are the economic costs to households of adopting sustainable management practices, and (2) what are the market costs of carbon sequestration if adoption is supported through projects developed in domestic or international carbon markets? Furthermore, we analyze the level and timing of revenues and costs for both households and a carbon project developer to investigate (3) what financing mechanisms could be deployed to finance development and implementation of sustainable grassland management projects in the carbon market context?

The structure of the paper is as follows. *Materials and Methods* presents the data sources and modeling methods applied. *Results* presents key results of the household and land resources survey

(*Households and Land Resources Survey Results*), carbon sequestration potential (*Carbon Sequestration Potential*), the modeling results on economic costs and financing options for herders (*Economic Costs of Grassland Carbon Sequestration*) and analysis of market costs and financing options for project developers (*Market Costs of Grassland Carbon Sequestration*). *Discussion* presents discussion of the study's findings and conclusions.

MATERIALS AND METHODS

Study Area

The study on which this paper is based was undertaken in Qinghai Province, on the Tibetan Plateau, China. Covering an area of approximately 2.5 million km² with an average elevation of more than 3500 meters above sea level and average annual temperature of less than 2°C, land cover on the Tibetan Plateau is dominated by alpine meadow and alpine steppe, which together cover more than 75% of the Plateau's land area (Zheng et al., 2000; Sheehy et al., 2006). In grassland ecosystems, most carbon is stored below ground in soils and plant roots (Ni 2002; Fan et al., 2007). Belowground and soil carbon density in alpine meadows is particularly large because of high biomass productivity and low average soil temperature that limits decomposition of organic matter and soil respiration (Zhao 2009). The Tibetan Plateau stores about 2.5% of the global soil carbon pool, but large amounts of carbon have been emitted to the atmosphere in recent decades due to grassland degradation (Ni 2002; Wang et al., 2002). Although the extent of degradation of the Plateau's grasslands remains contested (Harris 2009), as the source region of the Yellow, Yangtze and Mekong rivers, addressing grassland degradation on the Plateau has been given high priority in national environmental policy (State Council of the PRC 2011).

Commonly promoted measures for restoration of lightly and moderately degraded grassland in this region include seasonal resting of pastures and stocking rate management which result in improved biomass productivity, increased production of palatable forage and gradual improvement in soil chemical and physical structure (Dong et al., 2005a; Dong et al., 2005b; Dong et al., 2020). Fertilization and reseeding are recommended for heavily degraded grassland, and severely degraded grassland can be converted to cultivated perennial pasture, which produces about 2–3 times more biomass than native vegetation in the region (QPSB 2005; QPSB 2007; Zhang et al., 2012; Zhang et al., 2013). The study was undertaken in two adjacent communities in Zeku county, Qinghai Province, that had not previously implemented the aforementioned restoration measures.

Household and Land Resources Survey

Household survey data from 271 households in the two communities were collected in 2009–10 during the design of a carbon finance project. The communities were selected because of the relatively high proportion of degraded grasslands, which was taken as an indication of high carbon sequestration potential, and the interest of community leaders in addressing the challenges of grassland degradation and livelihood development. Within the

two communities the sample of households was self-selected based on the interest of each household to participate in the carbon finance project, and represented about 50% of households in the communities studied. For each household, data was collected on sheep (*Ovis aries*) flock and yak (*Bos grunniens*) herd size, flock and herd dynamics (i.e., mortality, off-take, reproduction), livestock management practices (e.g., supplementary feeding), and livestock production and grassland management costs and incomes. Livestock were converted to sheep units (SU) considering mature sheep as 1 sheep unit (SU), young sheep as 0.5 SU, mature yak as 5 SU and young yak as 2.5 SU, and 1 SU was assumed to consume 1.8 kg dry matter per day (Ministry of Agriculture 2002).

For each household, a land resources survey was undertaken that measured the area of all land plots owned by each household using GPS. Each plot was categorized as either lightly, moderately, heavily or severely degraded by applying criteria (e.g., vegetation cover, composition and height) developed on the basis of previous research on vegetation characteristics in the region (Liu et al., 2003; Wang 2005; Ma 2006; Dong et al., 2007; Ma 2007). At the same time, soil bulk density was measured and soil samples were collected for measurement of soil organic carbon (SOC) as described in Chang et al. (2014).

All surveys were carried out in partnership with the Northwest Institute of Plateau Biology of the Chinese Academy of Science, which has standing research clearance under the relevant Chinese and provincial laws and regulations. The research was conducted in accordance with national regulations and the policies of the Chinese Academy of Sciences under which prior approval by an ethics committee was not required. All herders gave free, prior and informed verbal consent to collection of socio-economic and land resources data and to sample soils in land under their management, and all personal data has been anonymized.

The analysis in this study uses household and land resources survey data from a sub-sample of the 271 households surveyed. Thirty four of the 271 households had no livestock, and were excluded from the analysis in this study which focuses on the response of animal husbandry incomes to alternative livestock and grassland management scenarios. The remaining households were divided into tertiles and the mean parameter values for the 79 households in the medium tertile were used to characterize a representative household for scenario analysis.

Modeling

Common household bioeconomic modeling approaches include econometric, decision rules based and mathematical programming approaches (Kruseman 2000). Each approach has its strengths, weaknesses and suitable use cases. The use case here requires modeling responses to management practices that are not present in the sample, which presents a challenge for econometric approaches (Jones et al., 2017). Mathematical programming models have been developed for extensive livestock systems on the basis of long-term research in Inner Mongolia (e.g., Behrendt et al., 2020). However, the lack of data to parameterize these models for livestock systems with different vegetation types and livestock species presents a challenge (Liu et al., 2020). Therefore, a heuristic rules-based

TABLE 1 | Biomass utilization rates, herd size and destocking rates in the baseline and five with-project scenarios modeled.

Scenarios	Warm season biomass utilization rate in Years 1–10 (%)[a]			Average cold season biomass utilization rate in Years 1–20	Sheep units per farm in years 1–10	Destocking rate (%)
	Lightly degraded grassland	Moderately degraded grassland	Average			
Baseline	81	81	81	78	207	0
Scenario A	50	30	39	50	147	29
Scenario B	40	30	35	50	128	38
Scenario C	40	20	29	50	110	47
Scenario D	30	20	25	50	92	56
Scenario E	20	20	20	50	73	65

[a]In years 11–20, all land plots can be grazed at 50% biomass utilization rate.

model was developed as a parsimonious approach in a data limited context.

Household level modeling involved three interrelated modules to model (1) the response of livestock production to alternative grassland management scenarios, (2) the response of SOC to changes in grassland management, and (3) the economic costs and benefits to the household livestock and grassland management enterprise in each scenario. For financial analysis of a carbon project, a separate financial model was developed. All calculations were performed in Microsoft Excel to facilitate interoperability between input data from the household survey, the outputs of SOC modeling, the livestock production model, and the economic and financial analysis.

Scenarios Modeled

The baseline scenario was represented by management practices, costs and incomes of the household livestock and grassland management enterprise using mean values of 79 households from the household survey. That is, the baseline scenario assumes that management practices and net incomes from the 2009–10 survey are unchanged compared to the survey data results over a 20-years simulation period. Five "with-project" scenarios were constructed to assess the effects of the household adopting carbon sequestering livestock and grazing management practices. The scenarios were determined on the basis of agronomic recommendations for restoration of degraded grassland in the project area, as confirmed by the results of carbon modeling (Chang et al., 2014).

Each with-project scenario assumed that all plots of heavily and severely degraded grassland are converted to cultivated perennial pastures planted with ryegrass (*Elymus nutans*) with application of inorganic fertilizers. For heavily degraded pastures, recommended protocols suggest fertilization with diammonium phosphate (75 kg per ha) in year 1 and urea (150 kg per ha) every 5 years thereafter, while for severely degraded pastures, fertilization with diammonium phosphate (75 kg per ha) in year 1 is followed by application of urea (150 kg per ha) in years 5 and 15, with reseeding in year 10 accompanied by application of diammonium phosphate (75 kg per ha) (QPSB 2005; QPSB 2007). In all with-project scenarios, reseeded and cultivated plots can be grazed at 50% biomass utilization rates in the cold season. Some heavily and severely degraded plots require additional fencing in order to prevent grazing by livestock in the warm season.

Lightly and moderately degraded grasslands can be restored by seasonal resting and reducing stocking rates (Dong et al., 2005a; Dong et al. 2005b; Dong et al. 2020). In each with-project scenario, lightly and moderately degraded plots are grazed in the warm season only. The five scenarios differ in the combinations of target biomass removal rates for warm season pasture in the first 10 years simulated, which vary from 20 to 50% in lightly degraded grassland and from 20 to 30% in moderately degraded grasslands (**Table 1**). In all scenarios, after 10 years of reduced grazing, lightly and moderately degraded warm season grassland will return to a state similar to non-degraded grassland and can be grazed at a 50% biomass removal rate in years 11–20. Biomass removal rates were estimated on the basis of sheep unit numbers multiplied by days of grazing in each season (cold season grazing 210 days, warm season grazing 150 days), assuming 1 SU consumes 1.8 kg of dry matter per day. Destocking rates were calculated as the percentage of baseline livestock numbers (converted to SU) that need to be sold in order to achieve the recommended biomass utilization rates in both seasons. Considering the land resources of the representative household modeled, these target biomass removal rates in each scenario imply destocking rates of between 29 and 65% compared to the baseline scenario (**Table 1**).

Modeling the Response of Livestock to Changes in Grassland Management

The livestock production module applies rules such that sheep and yak weight gain are determined by average warm and cold season biomass removal rates, and the total number of SU and herd structure are regulated by rules determining herd reproduction, survival and off-take.

For yak, experimental results show that the response of yak live weight gain (kg per season) to grazing intensity varies between warm and cold seasons, but in both cases, a quadratic equation provides a good fit to the data (Dong et al., 2006; Dong et al., 2015). That is, as grazing intensities reduce from a biomass utilization rate of around 0.8, live weight gain increases up to a biomass utilization rate of around 0.5, after which it declines as less digestible species dominate plant community composition (Zhao 2009). For sheep, research in the region reports a negative linear relationship between grazing intensities and live weight gain in both warm and cold seasons (Zhou 1995; Sun et al., 2015). Using data from the region on sheep and yak weights at different ages Zhao (2000); Luo et al. (2008), these relationships were

applied to estimate change in individual live weight gain under each scenarios with different grazing intensities.

None of the grazing intensity studies in the region reported the effects of grazing intensity on lamb or calf survival rates, adult mortality or reproduction rates. In the absence of data, it was conservatively assumed that these parameters remain constant across all scenarios with lamb and calf survival rates set at 0.9, sheep reproduction rates at 1.14 and yak reproduction rates at 0.66, and in line with household survey findings adult mortality rates were assumed to be constant at 0.02 for yak and 0.04 for sheep. Since herd performance and both production costs and revenues can be responsive to changes in these parameters, more research is required on these parameters to reduce uncertainty in the modeling results presented here.

Assuming land resources are unchanged, limiting grazing intensity is equivalent to imposing a cap on herd size. Maintaining herd size within the cap implies changes in offtake rate (i.e., proportion of the herd sold) and in herd structure. Livestock performance parameters were input into a rules-based herd dynamics model developed in visual basic for applications (VBA) in Excel to model the effects of a stocking cap on the structure of herds and offtake (Niu 2009). The input parameter values used in the herd dynamics model are shown in **Supplementary Table S1**. The model derives the total number of animals of each age that are sold and that remain in the herd at the end of each year based on the input parameters and the application of rules such that all rams ≥5 years old (yak bulls ≥4 years old) are sold and the ratio of adult rams to ewes is constant at 1:20 (or 1:30 for yaks). The weight of animals at each age was estimated using logistic curves fitted to data for Tibetan sheep and yaks (Zhao 2000; Luo et al., 2008). The modeled results for each year were used as input data to simulate herd and offtake dynamics for the subsequent year over a 20-year period, and the annual off-take of sheep and yak live weight was used as an input into the household economic model described below.

Modeling Carbon Sequestration Potential

Estimates of soil carbon sequestration rates derived from modeling using Century 4.5. This model has been used to simulated grazing effects on SOC in other studies in Asian grasslands (e.g., Wang et al., 2008; Chang et al., 2015). The calibration and validation of the Century model for the study site in the present study has been described in detail in Chang et al. (2014). In brief, the model was calibrated using data on climate and vegetation dynamics from Haibei Research Station, Chinese Academy of Sciences. The calibrated model was then applied to the research site using local meteorological data and assumed historical grazing intensities, and predicted SOC stocks for warm season grasslands were compared with measured stocks from the household land resources survey. The validated model was then used to estimate the response of SOC stocks to changes in management in each scenario simulated. The SOC sequestration rates associated with land plots characterized by different grazing seasons, biomass utilization rates and additional management measures applied to cultivated grass plots are detailed in **Supplementary Table S2**. Reductions in methane or nitrous oxide emissions due to improvements in forage

digestibility or reductions in herd size were not estimated, as changes in livestock and manure management GHG emissions would be small compared to SOC stock changes given the low density of livestock in the study area (Liu et al., 2017).

Household Economic Modeling

Economic modeling was accomplished using a partial budget approach, in which costs and incomes are compared between a baseline scenario and alternative scenarios with adoption of carbon sequestering management practices (Alimi and Manyong 2000). On the income side, only income from live animal sales and grassland rental were considered. The live weight of animals sold in each year was derived from the output of the livestock production model described in *Modeling the Response of Livestock to Changes in Grassland Management*. Other income sources (e.g., from sale of skins, wool, and dairy products), were not included due to a lack of data on their response to changes in grazing intensity. The only significant income source among these is dairy products, so it is assumed that any benefit in terms of increased milk production contributes to household consumption rather than cash income. Average 2009 prices in the study site (i.e., Chinese Yuan (CNY) 9.6 per kg live weight for sheep and CNY 9 per kg live weight for yak) were used to value the sale of animal live weight in all scenarios (in 2009, US$ 1 ≈ CNY 6.82). A single, uniform price was used for live animal sales, because although local markets do offer higher prices for animals with better body condition, herders are rarely able to achieve higher prices because of their poor bargaining position. Grassland rental income derived from the representative household renting out cultivated cold season pasture in excess of its own herd's needs, and was valued using 2009 market rates in the study site.

For each farm, some costs of production were assumed to be fixed on a unit area basis and some were variable depending on herd size. Costs estimated on a unit area basis included the costs of fencing maintenance, pest control and grassland rental, and average values for 2009 from the household survey were used (**Table 2**). Farm costs assumed to vary depending on herd size included the cost of veterinary medicines, oats and feed concentrate. The average cost per sheep unit from the household survey was used for each of these items. Among project implementation costs, destocking itself is assumed to be costless (and to bring in positive income), but additional investments are required in planting, fencing, and maintaining cultivated pasture through fertilization and reseeding. The costs of fencing, seeding and fertilization were based on 2009 cost estimates provided by local government agencies (**Table 2**).

Using the gross income from sale of live animals and grassland rental and the costs of livestock production and grassland management in each year of the 20-year simulation, the net present value of cash flows over 20 years were calculated for each scenario using Microsoft Excel. Discount rates of 4 and 12% were applied. The Chinese national standard for economic assessment of public investments in non-profit livestock investment projects is 7%, which reflects the mandated discount value for the use of public funds (Ministry of Agriculture 2009). The analysis here refers to the private discount rate to herders, where 4% reflects a

TABLE 2 | Cost parameter values applied in estimation of net income of the household in the scenarios modeled.

Cost item	units	Cost (CNY)
Annual farm costs[a]		
Fencing maintenance	per ha	11.00
Pest control	per ha	14.75
Grassland rental	per ha	6.60
Veterinary medicines	per SU	0.37
Oats	per SU	1.08
Feed concentrate	per SU	4.68
Project implementation costs[b]		
Grass cultivation in Year 1		
Heavily degraded grassland	per ha	1500
Severely degraded grassland	per ha	1650
Fencing of cultivated grass in year 1	per ha	112
Fertilization of heavily degraded grassland in years 5, 10, and 15 and severely degraded grasslands in years 5 and 15	per ha	420
Reseeding of severely degraded grassland in year 10	per ha	1500

SU, sheep units; CNY, Chinese Yuan.
[a]unit costs calculated from household survey.
[b]unit costs reported by Zeku County Animal Husbandry Bureau, 2009.

low estimate of the cost of borrowing, and 12% represents the discount rate of a risk averse borrower. For reference, in 2009 poverty alleviation loans carried interest of 3% and other agricultural loans 5–7%. It is assumed that herders would only adopt recommended practices if the net present value of their net income over 20 years after adoption is higher than the net present value of their projected baseline net income over 20 years, i.e., when **Eq. 1** holds true:

$$\sum_{t=1}^{20} r\{[P(LW_S - LW_B)] + (GR_S - GR_B)\} > 0 \qquad (1)$$

where r is the discount rate (i.e., either 4% or 12%); P is the price per kg live weight, which is assumed to remain constant across all scenarios modeled; LW_S is the total mass of animal live weight sold under each scenario S, summed across all years (t) in the 20-year simulation; LW_B is total live weight sold by the representative household in the baseline scenario; GR_S is the total income from renting out grassland in each scenario S, and GR_B is grassland rental income in the baseline scenario. The resulting estimate of the net present values of incremental income over 20 years represents the economic benefit (if NPVs are positive) or cost (if NPVs are negative) to herder households of adopting carbon sequestering practices. The economic model was also used to analyze the characteristics of households' cashflows in order to elucidate financing constraints faced by herders in adopting carbon sequestering practices and explore potential financing options.

Carbon Project Financial Model
In a carbon market context, the market cost of producing one tCO_2 emission reductions is higher than the economic cost to herders because of transaction costs and project financing costs (Cacho and Lipper 2006). Transaction costs include the initial costs of project identification, designing, approval and agreeing related legal contracts, and ongoing costs during project implementation, including facilitating activity planning with

participating households, monitoring, and verification and issuance of carbon credits. The assumed values of these transaction costs are shown in **Supplementary Table S3**. Furthermore, unless project developers have their own sources of finance, they may face additional financing costs if project development is financed with loans, as is commonly the case. A standard financial model quantifying the level and timing of capital and operating expenditures and revenues was programmed in Microsoft Excel to analyze the net present value of project developers' cashflows and identify the carbon price at which project developers' net return is positive, conditional on herders' incremental net incomes also being positive.

TABLE 3 | Key baseline characteristics of the household used for scenario modeling derived from household surveys.

Variable	Mean (minimum, maximum)	
Livestock resources		
Herd size (SU)	207 (150–266)	
Head of sheep	46 (0–150)	
Head of yak	39 (20–62)	
Land resources		
Total grassland area (ha)	79.02 (17–250)	
	Warm season	Cold season
Average % lightly degraded	14.2	13.1
Average % medium degraded	16.4	15.1
Average % heavily degraded	12.5	8.0
Average % severely degraded	6.8	13.8
Average biomass utilization rate (%)	80	
Grassland area rented out to others (ha)	5 (0–80)	
Grassland area rented in from others (ha)	36 (0–100)	
Incomes and expenditures		
% Income from live animal sales	77.5 (23–100)	
Gross income (CNY)	19,329 (3,700–92,850)	
Gross productive expenditures (CNY)	4807 (1,260–16,480)	
Net per capita income (CNY)	2769 (-73–12,707)	

Figures in parentheses represent the minimum and maximum among 79 households in the medium tertile.
SU, sheep units; ha, hectares; CNY, (Chinese Yuan, in 2009 CNY 1 ≈ US$ 0.1462).

TABLE 4 | Estimated carbon benefits for the household modeled from adoption of grassland management practices in each scenario (tonnes of carbon dioxide, tCO_2).

Scenario (% destocking)	tCO_2 per farm per year		tCO_2 over 20 years
	Years 1–10	Years 11–20	
Scenario A (0.29)	182.86	141.33	3242
Scenario B (0.38)	197.76	141.33	3391
Scenario C (0.47)	201.85	141.33	3432
Scenario D (0.56)	208.86	141.33	3502
Scenario E (0.65)	210.61	141.33	3519

TABLE 5 | Net present value (NPV) of net income and incremental net income over 20 years for the representative household in the baseline and with-project scenarios modeled (Chinese Yuan, CNY).

Scenario (% destocking)	NPV of 20 years' net income (4%)	NPV of 20 years' net income (12%)	NPV of incremental income (4%)	NPV of incremental income (12%)
Baseline	150,654	82,802	. . .	. . .
Scenario A (0.29)	270,043	119,578	119,389	36,776
Scenario B (0.38)	237,131	102,623	86,477	19,822
Scenario C (0.47)	195,039	83,491	44,385	690
Scenario D (0.56)	153,209	66,204	2,555	−16,598
Scenario E (0.65)	108,060	49,500	−42,594	−33,302

. . ., not applicable; NPV, net present value.

RESULTS

Household and Land Resources Survey Results

The 79 households in the medium tertile of the households surveyed had mixed herds of sheep (*Ovis aries*) and yak (*Bos grunniens*) ranging in scale from 150 to 266 SU, averaging 207 SU (**Table 3**). The average household had 79 hectares (ha) of grassland, half of which was used as warm season pasture, and half as cold season pasture. On average, 41% of grassland was heavily or severely degraded, 31% moderately degraded and 27% lightly degraded (**Table 3**). Compared to the average household in the two communities, which had 74 ha and 128 SU, the average household in this study had a similar area of grassland but a much larger livestock herd. Among the 79 households, the average household rented 36 ha from other households in the same or neighboring communities, and competition for rented grassland was strong. This may partly explain the self-selection of households for participation in the carbon project. Sale of live animals accounted for about 80% of household income. Survey data showed that baseline offtake rates were 0.31 for sheep and 0.15 for yaks, reflecting households' goals of increasing the size of their yak herds.

Carbon Sequestration Potential

Modeling results for soil carbon sequestration showed that sequestration rates varied depending on initial state of degradation and the season of grazing the baseline and project scenarios. The resulting sequestration estimates are between 0.01 and 7.08 tCO_2 per hectare per year for different land types grazed in different seasons in the baseline and project scenarios (see **Supplementary Table S2**). Applied to the land resources and recommended management practices of the household modeled, the estimated carbon benefits of adopting recommended practices range between 3240 and 3520 tCO_2 per farm over twenty years (**Table 4**).

Economic Costs of Grassland Carbon Sequestration

The model results suggest that cultivation of grass and adoption of rates of destocking between 29 and 56% are more attractive than the baseline at a discount rate of 4%, while a 65% destocking rate is not attractive at 4% (**Table 5**). At a discount rate of 12%, which might reflect higher costs of borrowing, risk averseness or a higher social rate of return, destocking rates of 29–47% are attractive compared to baseline net incomes (though 47% only marginally so), while destocking rates above 47% are not economically attractive compared to the baseline net income.

If the baseline nominal annual net income (CNY 11,085) is maintained for 20 years, the net income stream has a net present value (NPV) of CNY 82,000 at 12% or CNY 151,000 at 4%. At a 4% discount rate, the NPV of 20 years' net income for the lowest destocking rate scenario (Scenario A, 29% destocking) is 79% higher than the NPV of baseline annual income, while the NPV of 20 years' net income for the highest destocking rate scenario (Scenario E, 65% destocking) is 28% lower than the NPV of current income. At a 12% discount rate, the lowest destocking scenario has an NPV about 44% higher than the NPV of baseline net income, while the highest destocking scenario gives net income streams with an NPV 40% smaller than the NPV of baseline net income. The decline in the NPV of incremental net incomes as the rate of destocking increases is a result of the fact that a large part of total costs over time is fixed per farm (e.g., grass cultivation costs), while annual gross income decreases as the rate of destocking increases.
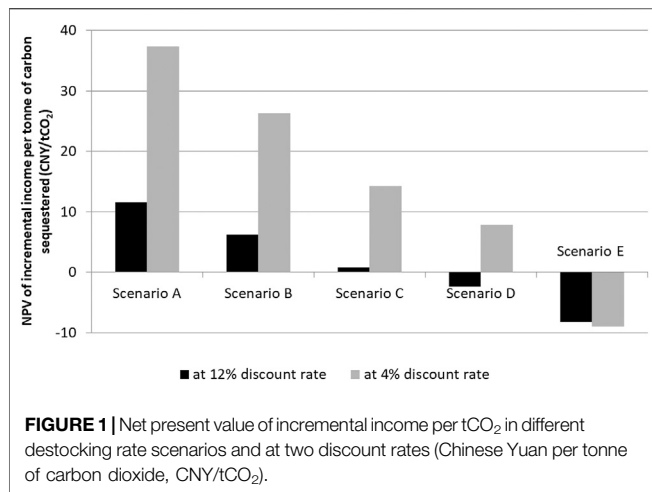
FIGURE 1 | Net present value of incremental income per tCO$_2$ in different destocking rate scenarios and at two discount rates (Chinese Yuan per tonne of carbon dioxide, CNY/tCO$_2$).

Figure 1 presents net benefit (positive values) or cost (negative values) to the herder household per tCO$_2$ sequestered over the 20-year period. As described above, for the three lowest levels of destocking (i.e., scenarios A, B, and C), there is a net economic benefit per tCO$_2$ sequestered, amounting to between CNY 0.77 to CNY 37.34 per tCO$_2$ depending on the discount rate used, while for the two highest destocking scenarios (i.e., scenarios D and E), the benefit per tCO$_2$ is between CNY −8.94 and CNY 7.82 depending on the discount rate applied.

Eq. 1 stated the assumption that households would only adopt improved management practices if the NPV of incremental incomes over 20 years is positive. **Table 6** shows the value of the payment per tCO$_2$ at which herders realize a positive return over the 20-year period. There is a positive return for the scenarios with the three lowest levels of destocking, indicating that the benefits of increased livestock income over time are higher than the costs associated with destocking, even without any payment for associated carbon sequestration benefits. For the higher destocking scenarios, at a 12% discount rate, a positive return is realized with relatively low payment per tCO$_2$e, and also with a 4% discount rate for Scenario E. The results shown in **Figure 1** and **Table 6** indicate that where different households need to destock at different rates in order to sequester carbon, there would be considerable differences in the economic cost of carbon sequestration.

However, analysis of cashflows suggests that even if the overall benefits of improving management are positive over a 20-year

period, herder households will face significant barriers in financing such improvements, depending on the timing of when costs and returns are realized. This is a key aspect in assessing the financial feasibility of adoption and identifying appropriate financial instruments to support adoption.

In the scenarios modeled, investments in grass cultivation and maintenance are the largest cost component. Of the implementation costs at farm level, 48% of total undiscounted grass cultivation costs occur in Year 1, 12% in Year 5, 28% in Year 10 and 12% in Year 15. In particular, the initial investment in grass cultivation in Year 1 (i.e., CNY 54,720) is about 15 times larger than other annual livestock enterprise costs for the representative farm. Total undiscounted grass cultivation and maintenance costs over 20 years (i.e., CNY 113,112) are 60–90% larger than total undiscounted annual livestock enterprise costs over 20 years for the five scenarios modeled.

Figure 2 shows accumulated net incremental income over 20 years for each scenario modeled. For destocking rates of 29–38% (i.e., the very low and low destocking scenarios), accumulated net income is lower than the baseline for the first 4 years, but is positive thereafter, showing relatively early returns to an increase in productivity and change in offtake rate despite the lower total number of livestock kept. For higher rates of destocking, accumulated net income remains lower than the baseline until year 16 (at 47% destocking) and year 19 (at 56% destocking), and at 65% destocking do not reach baseline levels within 20 years. In particular, at destocking rates above 38%, because of the need to restock, in the early years of restocking after Year 10 there is a decline in accumulated net incomes compared to the baseline. Because 65% is such a high rate of destocking, rebuilding the herd requires either decreased off-take or investment in purchase of breeding stock for a number of years, resulting in reduced incomes during the second decade modeled. While households destocking by 29% have 3 years of net income below the baseline net income in the first decade, and 1 year in the second decade, at 65% destocking there are 7 years with net incomes lower than in the baseline and 5 years in the second decade.

Overall, the modeling results suggest that lower levels of destocking are better able to balance livelihood and environmental objectives. For Scenarios A, B, and C, the higher net income compared to the baseline despite destocking are due in part to the assumed increase in productivity, and in part to the increase in offtake rates. In particular, baseline offtake rates for yak are around 15%, which then doubled to 30% in the modeled scenarios. Thus, with half the baseline yak numbers

TABLE 6 | Estimated payments to the household per ton of carbon at which net incremental incomes are positive in each with-project scenario modeled (Chinese Yuan, CNY).

Scenario (% destocking)	CNY/tCO$_2$ at 4% discount rate	CNY/tCO$_2$ at 12% discount rate
Scenario A (0.29)	−52.88	−28.5
Scenario B (0.38)	−38.30	−15.36
Scenario C (0.47)	−19.66	−0.53
Scenario D (0.56)	−1.13	12.87
Scenario E (0.65)	18.87	25.81

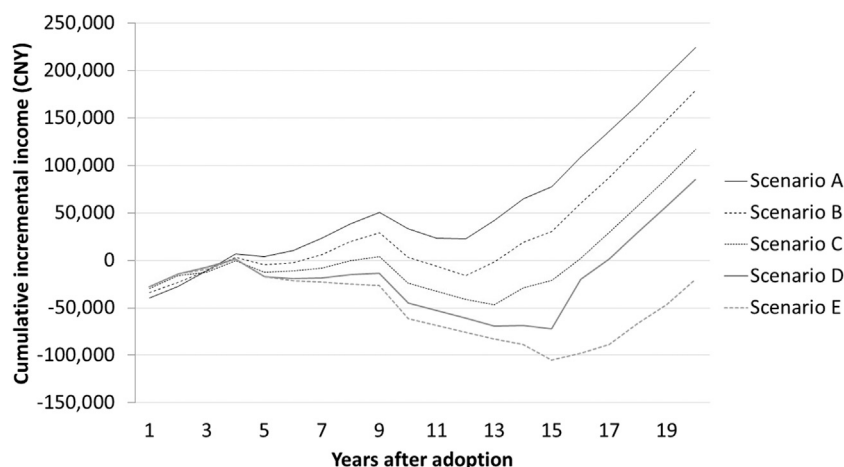*CNY, Chinese Yuan; tCO$_2$, metric tonnes of carbon dioxide.*

FIGURE 2 | Cumulative incremental net income of the household in the scenarios modeled (Chinese Yuan, CNY).

and a doubling in offtake, net incomes need not decline (depending on the age and weight of the animals sold). Furthermore, any increase in sheep productivity would lead to an increase in net income from the sheep raising enterprise of the household. Hence, the positive response of net incomes to destocking rates of 29–47% is partly due to the assumption of increased livestock marketing activity compared to the baseline. At high levels of destocking, households face two sources of opportunity cost: (a) reduced incomes due to reduced stocking levels in the first 10 years while grass is restoring; and (b) decreased income due to lower offtake rates or higher investment costs during the process of restocking in the second decade. In particular, if restocking is achieved through purchase of livestock, assuming that one year old sheep are purchased at the same price as herders' sales price, the implied total cost per household of restocking is between CNY 18,688 and CNY 131,868 for different scenarios modelled. Since these costs are significant in relation to annual net household incomes, restocking investments (and/or reduced offtake) are likely to be spread over several years.

Considering the level and timing of these cash flows, even at very high rates of destocking (e.g., Scenario E), households are unable to earn enough income from sale of livestock to cover the initial investment in grass cultivation. In absolute terms, the shortfall between livestock sales revenue and grass cultivation investment costs ranges between CNY 13,590 for Scenarios D and E, and CNY 25,494 for Scenario A. By comparison, 2009 net income per household was CNY 11,085, suggesting that even if all the proceeds of destocking are invested in grass cultivation *and* current consumption is financed from other (non-livestock) sources of income, households still face a financing gap equivalent to between 1 and 2.5 years of net income. This clearly represents a strong barrier to adoption, which could be overcome through appropriately designed financing.

In principle, herders have access to formal sector loans. Herders may apply for micro-credit loans from the Agricultural Bank of China and other providers. These loans

TABLE 7 | Maximum annual interest rate (%) at which the household could repay within 4 years a credit loan used to cultivate grass in the initial project year for each with-project scenario modeled.

Scenario (% destocking)	Annual interest rate (%)
Scenario A (0.29)	7.1
Scenario B (0.38)	4
Scenario C (0.47)	0.01
Scenario D (0.56)	2.5
Scenario E (0.65)	3

are typically between CNY 50,000 and CNY 100,000 at an interest rate of between 5 and 7% with a loan period of up to 8 years. Here, we assume that no guarantee or deposit is required; the household aims to repay the loan within 4 years so that fertilizer expenditures in Year 5 can be met; households use the loan to pay the costs of grass cultivation in Year 1; and aim to maintain a net household income of CNY 11,000. **Table 7** shows that at a very low (29%) destocking rate, households could potentially use available individual micro-loans to finance grass cultivation and smooth their net income streams. At other rates of destocking, interest rates must be subsidized. In the case of 47% destocking (medium destocking), almost free loans would be required. Studies of access to credit in rural Qinghai Province have found that rural finance institutions have a very low ratio of loans to deposits, as finance institutions seek to avoid longer-term, low-return investments in rural areas, resulting in limited access to loans for rural households (Song 2009, 2010). Rural households also lack assets that finance institutions accept as collateral against loans (Liu and Shi, 2012). Much of the subsidized micro-credit in the region is for short-term consumption loans only (Song, 2010). This suggests that for credit to support adoption of improved livestock and grassland management practices, financial products would need to be redesigned, conditions for access to credit revised, and policies developed to support
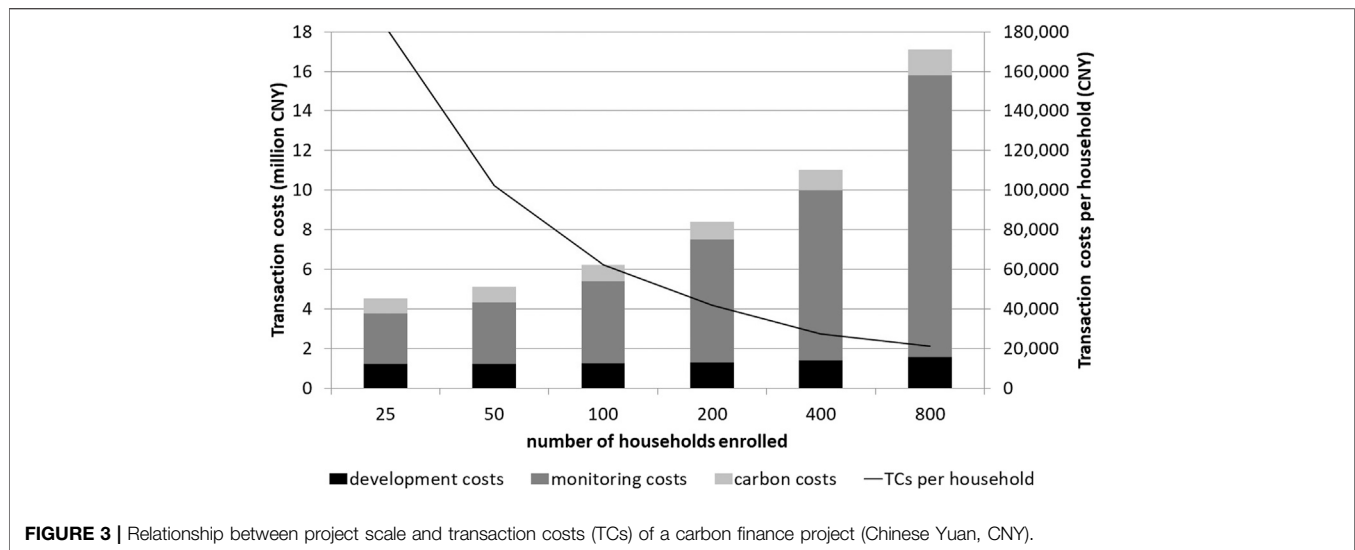
FIGURE 3 | Relationship between project scale and transaction costs (TCs) of a carbon finance project (Chinese Yuan, CNY).

provision of longer-term rural credit through loan guarantees and credit subsidies.

Availability of credit could assist households in making the initial investment in grass planting, and also in the fertilization of grass in Year 5. However, the CNY 24,330 investment required for reseeding in Year 10 of grass cultivated on severely degraded grassland coincides with a period of restocking, when households have reduced income from livestock sales (or increased outlays for purchasing breeding stock). In Year 10, therefore, households would have to finance both grass reseeding and purchase of livestock simultaneously. For the scenarios of medium, high and very high destocking, there are no savings accrued from incremental incomes during the first decade of implementation. Thus, unless destocking is limited to low rates, or households have significant income streams other than their livestock enterprise, credit financing is not a feasible option.

Market Costs of Grassland Carbon Sequestration

The preceding analysis focused on identifying the level of payment required for households to adopt the recommended practices. In this section, we estimate the market price of carbon at which grassland carbon projects would be feasible within a carbon market context. In addition to investment and opportunity costs at household level, this analysis considers transaction costs and finance costs faced by project developers, which have been identified as a significant additional cost in reaching smallholder producers with carbon payments (Cacho et al., 2013). Transaction costs are a key determinant of the incentives of carbon sequestration project developers in working with smallholder producers. Cacho and Lipper (2006) distinguish between *ex ante* and *ex post* transaction costs in the process of developing and implementing a contract. **Supplementary Table S3** itemizes the transaction costs modeled here. Analysis assesses the structure of carbon project costs; the effect of scale (in terms of area or number of households enrolled) on the cost of delivering verified carbon credits; and options for pre-financing project development costs.

Effect of Scale on Transaction Costs

Assuming a flat-rate contract per unit area (which incurs low negotiation costs), **Figure 3** shows that transaction costs per household (and thus per hectare) fall sharply as scale of adoption increases, beginning to plateau after about 400 households. Among the transaction costs assessed, project development costs are fairly invariant to project scale, as are verification and credit issuance costs, while the main component of transaction costs (i.e., monitoring costs) increases with scale. Project developers therefore have an incentive to develop larger projects and/or to secure sales of carbon credits in high-value niche markets. As the scale of a project increases, the diversity of actual costs faced by households increases, but negotiating contracts with each individual household would incur additional transaction costs.

Financing Options for Project Developers

Unless project developers have their own source of capital, project developers would have to finance upfront investment in the carbon sequestration project with a loan. Here, we assume that a project developer accesses a 5-year loan at 6% interest, and uses the loan to cover project development costs in Year 0, grass planting and maintenance costs in Years 1, 5, 10, and 15 and transaction costs over a 20-year project implementation period, and that destocking rates are below 47% and thus no incentive payments are required. **Figure 4** shows that as project scale increases, project developers' costs are dominated by the costs of planting grass. At small scale (25 households), grass planting costs account for 35% of total costs, while at large (800 household) scale grass planting costs increase to 75% of total costs. The cost of interest payments is between 8 and 11% of total costs at different scales, while other transaction costs decrease from 57% of total costs at small scale to 14% at large scale.
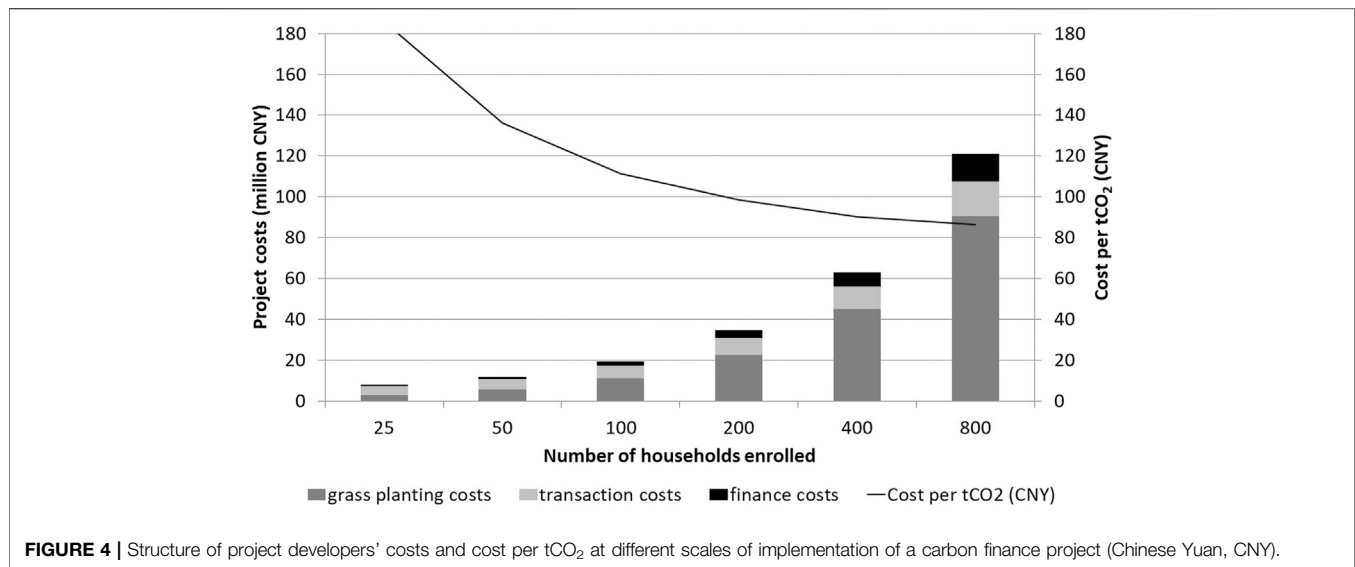
FIGURE 4 | Structure of project developers' costs and cost per tCO_2 at different scales of implementation of a carbon finance project (Chinese Yuan, CNY).

Grass cultivation and maintenance costs increase linearly with scale, and this imposes a significant investment burden as well as an investment risk if project developers pre-finance grass cultivation. The cost to project developers of producing each carbon credit, which in our modeling has not allowed any profit for project developers, is quite high in comparison to international carbon market prices (**Figure 4**, right axis). This indicates the low feasibility of full pre-financing by a project developer.

Recalling that at destocking rates up to 47%, the present value of 20 years' income stream is positive so households' main barrier to adoption is that revenue from the sale of livestock in Year 1 is insufficient to raise the finance needed to plant grass, an alternative financing option would be one in which the project developer pre-finances the gap between households' own investments and the full cost of grass planting in Year 1. A cost-sharing arrangement between project developer and participating households would reduce the project developer's investment needs, and grass cultivation costs would fall to about 50% of the project developer's total cost. The carbon cost curve would also shift downwards, enabling a project developer to achieve a positive return on investment at carbon prices between CNY 132–185 per credit at small scale (25 households), and between CNY 33–87 at large scale (800 households). Co-financing from a third party (e.g., government) would have a similar effect on the cost curve.

If all households are required to destock more than 47% of their herds in order to restore grasslands and sequester carbon, incentive payments to offset opportunity costs would be a significant additional cost. If payments are set at the payment per tCO_2 indicated in **Table 6** assuming a 12% discount rate for households, at small scale (25 households) incentive payments would increase total costs by 14 and 28% in Scenarios D and E, respectively, rising to 30 and 60% of total costs at a scale of 800 households. A project developer could achieve a positive return on investment at carbon prices between CNY 198–211 per credit at small scale (25 households), and between CNY 99–112 at large scale (800 households).

DISCUSSION

The technical mitigation potential of grassland soil carbon sequestration in developing countries is large Smith et al. (2007), Herrero et al. (2016), and soil carbon sequestration may have synergies with other policy objectives, such as biodiversity conservation, poverty alleviation and adaptation to climate change (Hoekstra et al., 2005; Alkemade et al., 2013; Joyce et al., 2013). However, developing operational payment mechanisms faces a number of challenges, including low rates of carbon sequestration per hectare, high transaction costs, non-permanence risks, poverty among land users, and the characteristics of project cash flows (Havemann, 2012; Smith et al., 2014; Godde et al., 2020).

A modeling approach was used to estimate the economic costs of adopting carbon sequestering management practices in the Tibetan Plateau, and the market costs of grassland carbon sequestration if projects are developed in the context of China's cap and trade mechanism. Compared to top-down modeling estimates Smith et al. (2007) suggesting that most economic potential in grasslands is feasible at costs above US$50/$tCO_2$, our study estimated the economic costs of carbon sequestration at between US$ −6.52 and US$3.78 per tCO_2. Market costs were estimated at between 12.70 and US$ 30.90, depending on the scale of implementation and the level of destocking required to restore grasslands and sequester carbon.

These results were based on modeling of a typical household using data from a non-random sample of households in two communities selected because of the high proportion of degraded grassland. The households surveyed had on average larger herds than the average household in the studied communities, but a similar grassland area. While causality cannot be established, this observation suggests that the costs of adopting sustainable grassland management practices for the average household analyzed may be higher than for the average household in the two communities, but that households with larger herds and/or higher stocking rates on their contracted grasslands may be more

strongly motivated to find ways to improve livestock production and address grassland degradation. Although carbon sequestration projects are likely to target atypical areas such as the selected study site where the presence of grassland degradation indicates potential for carbon sequestration, our specific cost estimates cannot be extrapolated to the wider region. Since the survey was conducted, relative prices of livestock and grass cultivation have not changed significantly, but grassland management policies have developed, and herders now receive incentive payments of CNY 37.5 per ha to maintain stocking rate balance and CNY 262/ha for grazing exclosure applied to heavily and severely degraded land (Huangnan Prefecture Government, 2020). If these payments have effectively incentivized herders to reduce stocking rates, the effect would be to reduce the destocking rates required to sequester soil carbon, thus reducing economic costs to herders of adopting sustainable grazing management practices. However, no ex post assessments have been conducted to understand the effects of incentive payments in the study area. Despite these uncertainties, as well as the non-random sample, the analysis presented here can be used to highlight where correlations exist between key factors likely to affect the feasibility of households adopting carbon sequestering management practices and factors affecting the feasibility of payment schemes for carbon sequestration in grasslands.

The model used here was developed based on an empirical case study, but in a context of limited available data on responses to changes in management practice (Liu et al., 2020). In particular, data on the effects of reduced grazing intensity on livestock performance parameters in the region is sparse. However, it is clear that improving livestock management practices to reduce lamb and calf mortality, improving reproductive performance and increasing animal weight gain, and increasing market access are important complements to the adoption of improved grazing management practices (Kemp 2020). Schemes involving payments for carbon sequestration services from improved grassland management, particularly in developing countries where livestock performance is suboptimal and market linkages are weak, would benefit from addressing the technical and institutional supporting conditions for improved grazing management as part of scheme design. In the case here, although markets were offering higher prices for animals in better body condition, marketing arrangements left herders with limited bargaining power and they were often unable to obtain higher prices. Similar marketing constraints are common in Asia's grasslands, indicating that addressing market failures to enable herders to access higher value markets, while also improving the quality of livestock products, would have important implications for the development of incentives to reduce grazing intensity (Briske et al., 2015).

Similar to a number of other studies in China's grasslands, the analysis here suggests that herders' net incomes could increase over time if stocking rates are reduced (e.g., Kemp and Michalk, 2011; Li et al., 2015; Li et al., 2018; Badgery et al., 2020; Kemp et al., 2013). However, studies have also found that herders have their own understanding of suitable stocking rates, suggesting that herders' decisions may consider factors other than profitability (Hou et al., 2014). Despite the relatively low economic costs of grassland carbon

sequestration in this study, detailed analysis of cash flows highlights several barriers to adoption and challenges for designing financial support measures. In the example here, both investment costs and opportunity costs are significant barriers to adoption by households. Where a considerable proportion of grazing land is heavily or severely degraded, initial investment costs may be large. Financing these investments through loans is likely only feasible if public subsidies are made available to reduce interest rates, which is similar to findings by (Pan et al., 2021). Additionally, it may require that conditions for access to credit finance are significantly revised to remove barriers due to collateral requirements and short repayment periods that are common requirements for rural finance (Jahan et al., 2019). Elsewhere in Asia, degradation driven by overgrazing may be widespread but not so severe (e.g., Densambuu et al., 2018). In such situations, grassland rehabilitation may not incur large direct costs in grass cultivation, but reducing herd sizes could still impose significant opportunity costs on herders. Upfront investment in measures to increase animal and herd productivity and market access, or investments in road and water infrastructure to enable access to underutilized pasture, would have the same effect on financial feasibility as the grass cultivation measures in this case study.

The need for upfront investment in improved management practices represents a significant risk for private investors or other results-based carbon funds, and limits the potential for results-based carbon finance as the primary source of investment in grassland carbon sequestration. When faced with such risks, investors' discount rates and profit requirements are likely to be much higher than assumed in the analysis here (Covell, 2011), resulting in a much higher minimum carbon price to attract investors. Public funding of initial investments with carbon finance support for subsequent project expenses can reduce this risk. In China, where government has invested large sums in grassland management every year (ADB, 2014), carbon finance can potentially be coordinated with public investments. In other contexts, sources of climate finance that are able to bear upfront investment costs will be more relevant that results-based carbon or climate finance. More generally, with innovative project types, which investors perceive as riskier than with established carbon project types, public investment to finance public goods aspects of early pilot projects, and green finance mechanisms (e.g., loan facilities that accept future carbon credits as collateral, or public-private carbon funds with a subordinated public equity stake) will be necessary to reduce investor risk and increase investor incentives to engage in the grassland sector.

These findings suggest that design of public policies to support grassland carbon sequestration in developing Asia should (a) consider integrated interventions to support grassland and grazing management, livestock management and livestock product marketing; and (b) consider the potential roles of a range of financial instruments within the broader financing landscape. Where initial investment costs are high, public investments may be used either to directly support adoption or to increase access to rural credit through credit subsidies or loan guarantees. Results-based payments, whether from fiscal, carbon or climate finance sources, can potentially play a complementary role in incentivizing continued adoption of

good grazing management practices, but are not likely to be effective as the sole source of finance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

AW conceptualized the study, analyzed the data and led drafting the manuscript. SW led data collection and contributed to drafting the manuscript. LL contributed to drafting the manuscript. XC collected the data and contributed to drafting the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.657608/full#supplementary-material.

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