

Article

Livestock Pressure, Soil Organic Carbon, and Herder Income in Mongolian Rangelands: Dual-Scale Empirical and Scenario-Based Evidence

Enkhbayar Davaatseren ¹, Tsolmon Sodnomdavaa ^{2,*} , Erkhbayar Enkhbayar ¹, Sainbuyan Bayarsaikhan ³, Urtnasan Mandakh ⁴  and Miyegombo Dorj ⁵

¹ Nomadic Industrial Cluster System NICS LLC, Ulaanbaatar 14240, Mongolia; enkhbayar.d@nicsda.com (E.D.); 2015c.erkhetbayar.e@shineue.edu.mn (E.E.)

² Department of Finance and Economics, Mandakh University, Ulaanbaatar 16061, Mongolia

³ Department of Geography, School of Art and Sciences, National University of Mongolia, Ulaanbaatar 14201, Mongolia; sainbuyan.b@num.edu.mn

⁴ Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar 15170, Mongolia; urtnasanm@mas.ac.mn

⁵ “Tavannud” Mongolian Cultural Foundation NGO, Ulaanbaatar 14240, Mongolia; miyegombo@gmail.com

* Correspondence: tsolmon@mandakh.edu.mn

Abstract

Mongolian rangelands face interacting ecological and livelihood pressures, including livestock pressure, vegetation change, soil-carbon dynamics, household income variability, and inefficiencies in livestock by-product recovery. This paper examines whether observed administrative and household data, field-observed pilot-area audit evidence, satellite-derived/backcast vegetation indicators, model-reconstructed ecological trajectories, econometric associations, machine-learning diagnostics, Monte Carlo uncertainty outputs, and scenario-based carbon-finance calculations are consistent with a study-specific ecological–economic feedback framework in Mongolian pastoral rangelands. The analysis combines observed livestock and household data, satellite-derived vegetation indicators, field-anchored soil organic carbon (SOC) information, climate controls, and pilot-area by-product audit evidence in a dual-scale framework comprising nine pasture-user groups in Öndörshireet Soum, Töv Aimag, and a national soum-level panel for 2002–2024. SOC, above-ground biomass (AGB), and below-ground biomass (BGB) trajectories are treated as model-reconstructed series rather than independently observed annual field measurements. Fixed-effects panel models are used to estimate conditional associations, while machine-learning models assess predictive consistency within reconstructed data structures. Under the fitted full specification, the best-performing national-panel model reports an out-of-sample R^2 of 0.942 for model-reconstructed SOC; this value is interpreted as high internal predictive consistency within the reconstructed SOC panel, not as independent validation of observed annual SOC change. Because the SU/SOC ratio mechanically contains SOC, the full-specification predictive results are subject to leakage risk, and leakage-free validation is needed for a more conservative assessment of predictive performance. Panel estimates suggest that vegetation condition is positively associated with $\ln(\text{household income})$, while the by-product waste ratio is negatively associated with $\ln(\text{income})$, conditional on fixed effects and model specification. Scenario-based carbon-finance outputs, framed with reference to Verra’s VM0042 Improved Agricultural Land Management methodology, vary materially with compliance, carbon price, weighted average cost of capital, and revenue-sharing assumptions; these outputs are illustrative sensitivity calculations and do not demonstrate VM0042 compliance, project eligibility, project-registration readiness, verified emission



Academic Editor: Ligang Xu

Received: 28 May 2026

Revised: 23 June 2026

Accepted: 26 June 2026

Published: 29 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

reductions, or credit-issuance readiness. The findings are associational, reconstruction-dependent, and scenario-based. They support an analytical framework rather than establish a closed causal loop.

Keywords: rangeland degradation; soil organic carbon; pastoral livelihoods; grazing pressure; ecosystem governance; carbon finance; scenario analysis; Mongolia

1. Introduction

Mongolia's rangelands represent a large temperate dryland pastoral social–ecological system. They support livestock-based livelihoods, forage provision, biodiversity habitat, soil organic carbon storage, erosion control, and other ecosystem-service functions that underpin rural pastoral economies. These rangelands are embedded in a coupled social–ecological system in which household welfare, grazing institutions, climate variability, vegetation condition, soil processes, and value-chain efficiency interact across multiple spatial and temporal scales. Dryland research has shown that land degradation rarely results from a single driver; instead, degradation outcomes emerge from the interaction of climate variability, land-use pressure, institutional conditions, and livelihood constraints [1]. In grazing systems, ecosystem-service delivery is similarly shaped by interactions among grazing intensity, climate, soil properties, biodiversity, and management context [2]. Mongolia, therefore, provides an important empirical setting for examining how pastoral livelihoods, rangeland conditions, soil-carbon dynamics, and carbon finance design intersect.

The specific problem addressed in this study is the coexistence of rangeland degradation risk, livestock pressure, unstable or declining rural incomes, and incomplete recovery of livestock by-products. The magnitude of rangeland degradation in Mongolia remains contested because estimates differ across definitions, indicators, ecological zones, and assessment methods [3]. Nevertheless, systematic review evidence indicates that climate variability and grazing pressure are frequently identified as important drivers of rangeland change [3–5]. Recent quasi-experimental evidence further suggests that climate variability explains a substantial share of long-term variation in Mongolian rangeland primary productivity, while herd pressure may still have measurable effects over shorter time scales [6]. On the livelihood side, rangeland degradation has been associated with lower livestock-related income outcomes, although the effects vary by income definition, production system, and household adaptation capacity [7]. Within this context, the present paper uses a study-specific ecological–economic feedback framework as a motivating analytical structure, not as an established theory or as proof of a causal mechanism. The framework links ecological stress, livelihood constraints, grazing pressure, production inefficiency, and household income, treating these relationships as associative and context-dependent.

The existing literature provides important but fragmented evidence. Mongolia-specific studies have examined rangeland degradation, vegetation dynamics, grazing pressure, climate variability, pastoral vulnerability, community-based rangeland management, and institutional conditions shaping herder decisions [3,6,8–10]. Remote sensing studies widely use the Normalized Difference Vegetation Index (NDVI) as an indicator of vegetation condition, but NDVI is not a direct measure of all vegetation, soil, or ecosystem processes [11]. Soil organic carbon (SOC), above-ground biomass (AGB), and below-ground biomass (BGB) are also difficult to observe annually at scale; therefore, studies that rely on field-anchored reconstruction must distinguish observed measurements from model-reconstructed trajectories. However, less is known about how livestock pressure, satellite-derived/backcast vegetation indicators, field-anchored soil-carbon reconstruction, household income, live-

stock by-product recovery, and climate controls can be jointly examined within a dual-scale empirical framework. A second gap concerns the production-efficiency channel. Pastoral livelihood studies often focus on herd size, livestock sales, meat, milk, wool, cashmere, or aggregate farm income, while the non-recovery or low-value recovery of livestock by-products has received limited systematic attention. A third gap concerns carbon-finance design: there is limited scenario-based evidence on how governance, compliance, monitoring, and revenue-sharing assumptions may shape rangeland carbon-finance outcomes in pastoral systems.

This study is guided by a cautious ecological–economic feedback framework. Household income constraints and exposure to climate and market risks may encourage households to maintain or expand herd numbers as a risk-management strategy. Where collective grazing rules, monitoring mechanisms, and incentives are weak or unevenly enforced, individually rational herd-management decisions may contribute to aggregate grazing pressure, a problem consistent with common-pool resource theory and pastoral governance research [10,12,13]. Higher livestock pressure may be associated with poorer vegetation conditions and less favorable soil-carbon outcomes, although these relationships are expected to vary by ecological zone, climate conditions, soil type, and management context. Lower vegetation conditions may also be associated with weaker livestock productivity and lower recoverable value from livestock products and by-products. The study, therefore, examines whether observed data, satellite-derived/backcast indicators, model-reconstructed SOC, by-product waste, and household income align with the proposed feedback framework under specific empirical and scenario assumptions. Causal closure is not claimed.

The objective of the paper is to estimate whether livestock pressure, vegetation condition, model-reconstructed SOC, by-product waste, and household income are systematically associated in Mongolian rangelands, and to assess how alternative compliance and revenue-sharing assumptions shape scenario-based carbon-finance outcomes. The study combines a local pasture-user group (PUG) panel from Öndörshireet Soum, Töv Aimag, with a national soum-level panel for 2002–2024, using observed livestock and household data, satellite-derived/backcast vegetation indicators, field-anchored SOC reconstruction, climate controls, and pilot-area by-product audit evidence. Sheep Units (SUs) are used to express livestock pressure in a standardized livestock-equivalent metric, and rural household income is deflated using the Consumer Price Index (CPI). Three research questions (RQs) guide the analysis. RQ1: How are livestock pressure, vegetation condition, and soil organic carbon associated across local and national-scale rangeland panels? RQ2: Is vegetation condition associated with household income after accounting for herd size, by-product waste, and time effects? RQ3: Under explicit scenario assumptions, how sensitive are potential carbon-finance and household-feasibility outcomes to compliance, monitoring, carbon price, and revenue-sharing parameters?

The paper makes three contributions. First, it provides empirical evidence on the joint association between livestock pressure, vegetation condition, model-reconstructed SOC, by-product waste, and household income in Mongolia using a dual-scale panel structure. Second, it contributes methodologically by integrating satellite vegetation indicators, field-anchored soil-carbon reconstruction, household information, livestock data, and climate controls within an observational and reconstruction-based modeling framework. Third, it provides a scenario-oriented policy contribution by assessing how governance, compliance, and revenue-sharing assumptions may affect carbon-finance outcomes under the applicable version of Verra’s VM0042 Improved Agricultural Land Management methodology [14], conditional on stated assumptions. This reference to VM0042 defines the methodological context for scenario analysis only and does not imply project eligibility, validation, project registration readiness, or credit issuance readiness. The remainder of the paper presents

the study area, conceptual framework, data and variable construction, modeling strategy, empirical results, scenario analysis, and implications for rangeland governance and carbon-finance design.

Figure 1 presents descriptive national trends in livestock numbers and rural household real income for 2002–2024 that motivate the empirical analysis. The figure shows that livestock numbers and rural income moved through repeated climate-shock periods, including major dzud years, rather than following a simple linear trajectory. These descriptive patterns do not establish causality; instead, they motivate an examination of whether livestock pressure, vegetation condition, model-reconstructed SOC, by-product recovery, and household income are systematically associated across local- and national-scale panels.

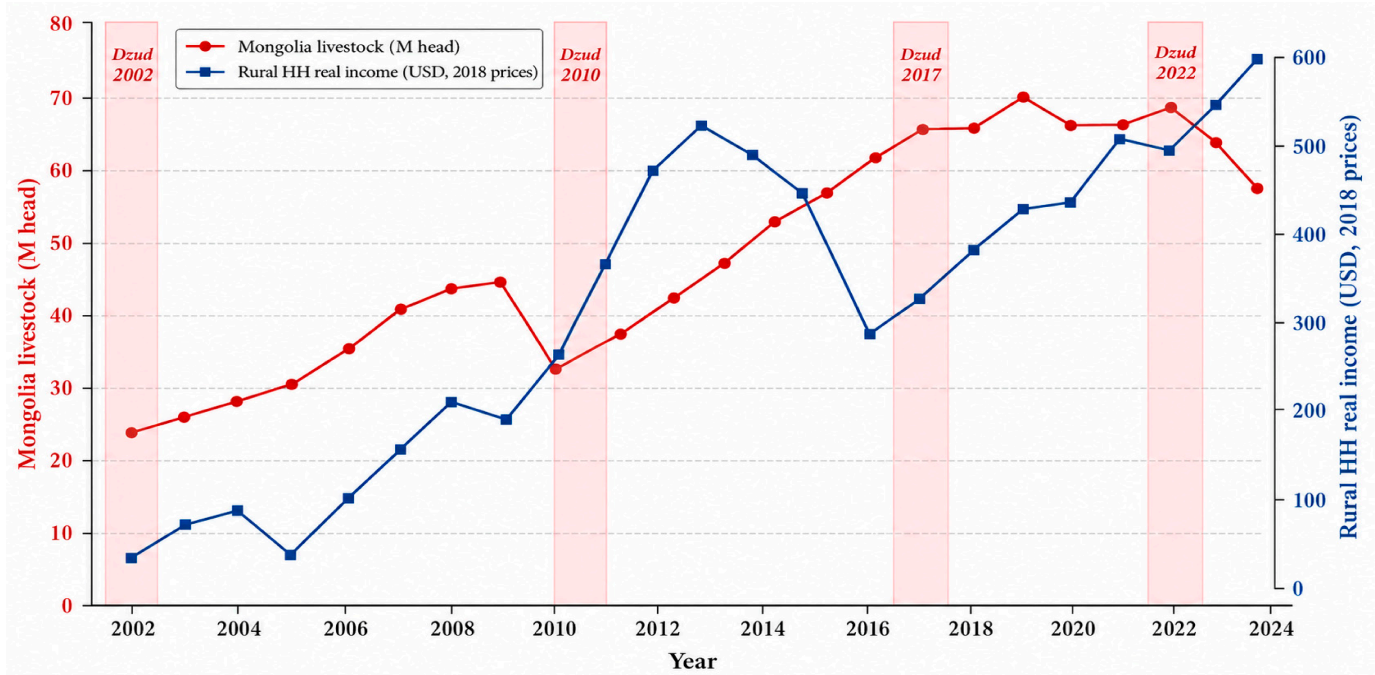


Figure 1. Descriptive trends in Mongolian national livestock numbers and rural household real income, 2002–2024. The left axis reports total livestock numbers, and the right axis reports rural household real income. Pink shading marks four dzud cycles (2002, 2010, 2017, 2022). Source: National Statistics Office of Mongolia, Statistical Yearbook 2024, and Household Socioeconomic Survey [15,16].

2. Study Area

The pilot study area is Öndörshireet Soum in Töv Aimag, Mongolia. The site serves as the local empirical setting to examine relationships among grazing pressure, vegetation condition, model-reconstructed SOC, household income, livestock by-product recovery, and scenario-based carbon-finance outcomes. Öndörshireet is relevant for this study because it represents a livestock-based pastoral production setting in which household income, herd-management incentives, rangeland condition, and by-product recovery can be examined jointly at the pasture-user group level.

The local analytical unit is the pasture-user group (PUG). The manuscript uses 9 PUGs in Öndörshireet as the basis for the local PUG-year panel. These PUGs provide the spatial and institutional structure through which household livestock data, vegetation indicators, reconstructed SOC and biomass trajectories, and field audit information are organized [17]. The PUG structure is important because grazing pressure and restoration incentives are not only household-level issues; they are also shaped by collective access rules, monitoring capacity, local coordination, and the distribution of costs and benefits across herder groups.

The local ecological setting is treated as a dryland pastoral rangeland system without adding unverified coordinates, area values, or ecological-zone labels. The study area is characterized analytically as a livestock-dependent rangeland setting in which vegetation condition, forage availability, soil-carbon dynamics, and household livelihoods are closely linked. This makes the site suitable for examining whether observed household and livestock data, field-anchored ecological reconstruction, and by-product audit information align with the proposed ecological–economic feedback framework.

The local PUG panel is linked to the national soum-level panel in a dual-scale design. The Öndörshireet PUG panel provides pilot-area evidence with relatively detailed household, livestock, and field-audit information. The national soum-level panel provides broader contextual variation across Mongolia over the same 2002–2024 study window. The national panel does not make the Öndörshireet waste-ratio findings nationally representative, and the local pilot results should not be generalized across Mongolia’s ecological zones without multi-site validation. Instead, the two panels serve different analytical purposes: the local panel supports detailed pilot-area analysis, while the national panel provides broader calibration and comparison for reconstructed ecological and livestock-pressure patterns.

3. Conceptual Framework: A Study-Specific Ecological–Economic Feedback Framework

3.1. Rangeland Pressure, Ecosystem Services, and Ecological Feedbacks

This section develops the conceptual framework for interpreting the empirical analysis. The framework treats the relationship among livelihood constraints, herd-management incentives, grazing pressure, vegetation condition, model-reconstructed soil organic carbon, livestock quality, by-product recovery, and household income as an association rather than a closed causal mechanism. It does not assume that these relationships constitute a closed causal loop. Rather, it asks whether observed data, model-reconstructed ecological trajectories, model-based diagnostics, and scenario-based calculations are consistent with a reinforcing ecological–economic association under specific institutional and climatic conditions.

The first component of the framework concerns rangeland pressure and ecosystem services. Mongolian rangelands provide forage for livestock, soil carbon storage, biodiversity habitat, erosion-control functions, water retention and soil function services, and livelihood support. These ecosystem services are interdependent: vegetation condition affects forage availability and livestock productivity, while vegetation cover and root biomass contribute to soil protection and soil-carbon dynamics. Declines in vegetation condition may therefore signal broader ecosystem-service stress, although satellite-derived vegetation indicators should be interpreted as indicators rather than direct measurements of all ecosystem processes.

The starting point is common-pool resource theory. In shared rangeland systems, household-level incentives may diverge from collective ecological outcomes when access rules, monitoring, sanctioning, and collective-choice arrangements are weak or unevenly enforced [12,13]. In pastoral systems, however, this logic must be applied with caution because mobility, reciprocity, social relations, forage availability, and ecological variability also shape herders’ grazing and herd-management decisions. Recent evidence from Mongolia shows that rules, social capital, forage availability, and local social–ecological context influence pastoral management decisions, cautioning against one-size-fits-all governance explanations [10].

Within this framework, household income constraints and exposure to climate and market risks may encourage households to maintain or expand herd numbers as a risk-

management strategy. Such responses can be rational at the household level, especially where livestock serves as an income source, a productive asset, an insurance mechanism, and a form of social security. If many households respond similarly, however, aggregate livestock pressure may increase relative to local vegetation recovery capacity. The ecological consequences are likely to depend on precipitation, temperature, dzud shocks, soil conditions, ecological zone, and local management. This interpretation is consistent with dryland research showing that grazing effects are mediated by climate, soil, biodiversity, and aridity thresholds [1,2,18].

Vegetation condition is central to this framework because it links grazing pressure, forage availability, livestock productivity, and soil-carbon dynamics. Satellite-derived vegetation indices, such as the Normalized Difference Vegetation Index, are widely used to assess ecological responses to environmental change, although they should be interpreted as indicators rather than as direct measures of all ecosystem processes [11].

In this study, vegetation indicators are used alongside field-anchored soil-carbon information, livestock data, household data, and climate controls to assess whether livestock pressure and vegetation condition are associated with model-reconstructed soil-carbon and income outcomes.

3.2. Production Inefficiency and Value-Chain Loss

The second component of the framework concerns production inefficiency and value-chain losses. Pastoral livelihood studies commonly focus on herd size, livestock sales, meat, milk, wool, cashmere, and farm income. Less attention is usually given to the non-recovery or low-value recovery of livestock by-products such as hides, wool, offal, blood, bone, fat, and other animal-derived materials. This omission matters because household income depends not only on the number of animals owned or sold but also on the value recovered per animal.

The present study treats the waste ratio as an empirical indicator of production inefficiency in the Öndörshireet pilot area. A higher waste ratio is expected to be negatively associated with realized household income if unrecovered or rejected by-products reduce the value obtained from livestock production. This expectation is consistent with the broader finding that rangeland degradation may reduce livestock product sales and farm income. However, the specific by-product recovery channel remains an empirical question for the study at hand rather than a settled claim in the literature [7].

The conceptual link to land-use pressure is therefore indirect. If households receive low realized income per animal, they may face stronger incentives to rely on herd numbers rather than productivity, quality improvement, or value-added recovery. This relationship is plausible, but it is not assumed to be established. The empirical analysis, therefore, examines whether by-product waste is associated with household income, controlling for herd size, vegetation condition, and time effects. Because the by-product audit is pilot-area evidence, its transferability across Mongolia's ecological zones and livestock value chains requires multi-site validation.

3.3. Environmental Feedback-Loop Losses

The framework also recognizes potential environmental feedback-loop losses. If vegetation conditions decline over multiple years, forage availability may weaken, livestock condition and product quality may deteriorate, and pressure to maintain or increase herd numbers may intensify. In turn, higher grazing pressure may be associated with greater vegetation stress and less favorable soil-carbon outcomes, depending on rainfall, temperature, dzud exposure, soil type, mobility, and local management. The manuscript treats

these patterns as possible reinforcing associations rather than as proof of a deterministic ecological-collapse pathway.

Soil organic carbon is central to this feedback framing because it is linked to soil fertility, water retention, vegetation recovery, and long-term rangeland resilience. However, annual soil organic carbon trajectories in this study are model-reconstructed rather than independently observed annual field measurements. For that reason, the reconstructed soil-carbon decline is interpreted as an analytical signal conditional on the reconstruction method, rather than as direct annual field evidence. The framework, therefore, separates observed household and livestock data, satellite-derived/backcast vegetation indicators, model-reconstructed ecological trajectories, econometric associations, machine-learning diagnostics, and scenario-based carbon-finance calculations.

3.4. Governance, Compliance, and Carbon-Finance Feasibility

Governance and compliance are central to rangeland restoration and carbon-finance feasibility. Restoration practices may be technically plausible, but their ecological and financial outcomes depend on whether households, pasture-user groups, local authorities, and implementing institutions can sustain agreed grazing practices, monitoring, reporting, and benefit-sharing arrangements over time. In payment-for-ecosystem-services and result-based payment schemes, outcomes depend on program design, monitoring credibility, opportunity costs, payment conditionality, payment continuity, and local institutional context [19–22].

In this study, the Nomadic Industrial Cluster System is treated only as one illustrative scenario-based governance and carbon-finance architecture, not as a validated, superior, or proven solution. The scenario architecture includes monitoring, restoration incentives, digital participation tools, livestock traceability, result-based payments, by-product recovery, and equity-stewardship mechanisms linked to value-chain development. These components are evaluated under explicit assumptions to examine how alternative compliance and revenue-sharing parameters could affect scenario-based carbon-finance outcomes and household-level incentives.

The carbon-finance component is framed with reference to the applicable version of Verra's VM0042 Improved Agricultural Land Management methodology, subject to version-specific requirements at the time of submission. VM0042 provides a methodology for quantifying greenhouse gas emission reductions and soil organic carbon removals associated with improved agricultural land management practices, including grazing-related practices where applicable [14,23]. This reference supports only the methodological scope of VM0042. It does not establish that the present scenario is eligible, validated, registered, compliant, or ready for credit issuance. Any operational governance model would require data on observed compliance, participation, monitoring, payment, leakage, permanence, and ecological response before project registration or credit issuance claims could be supported.

3.5. Analytical Expectations

The conceptual framework leads to four analytical expectations. These are analytical expectations, not confirmed results. First, higher livestock pressure is expected to be associated with poorer vegetation conditions and less favorable model-reconstructed soil-carbon outcomes, conditional on climate and time-varying controls. This expectation follows from the dryland and grazing literature showing that ecosystem-service delivery depends on interactions among grazing pressure, climate, soil, and biodiversity [2,18].

Second, better vegetation condition is expected to be positively associated with household income, although this relationship may be mediated by livestock productivity, herd

structure, market access, and local ecological conditions. Third, higher by-product waste is expected to be negatively associated with household income because lower recovery of animal-derived products may reduce realized value per animal. Because systematic peer-reviewed evidence on this specific channel in Mongolian pastoral systems remains limited, this expectation is treated as a study-specific empirical proposition.

Fourth, governance and compliance assumptions are expected to influence scenario-based carbon-finance outcomes because monitoring, conditionality, opportunity costs, and payment credibility affect participation incentives in ecosystem-service payment schemes [19,21,22]. The panel models assess whether the observed and reconstructed evidence is consistent with the proposed ecological–economic feedback framework. The scenario analysis then evaluates the sensitivity of potential carbon-finance and household-level outcomes to alternative assumptions about compliance, monitoring, and revenue sharing. These expectations guide the empirical analysis without implying causal identification, verified project eligibility, or credit-issuance readiness.

4. Data and Variable Construction

This section describes the data sources, variable construction procedures, and main limitations of the empirical inputs used in the panel models, machine-learning diagnostics, and scenario analysis. The section distinguishes observed administrative and statistical data, field-observed data, satellite-derived/backcast vegetation indicators, model-reconstructed ecological variables, machine-learning outputs, and scenario-based parameters. This distinction is necessary because the variables used in the empirical and scenario components do not have the same evidentiary status. The variable construction logic linking outcomes, livestock variables, ecological variables, climate indicators, price variables, management variables, narrative cognition framing, and scenario carbon parameters is summarized in Appendix A.2.

4.1. Observed Administrative and Statistical Data

Annual national, aimag-level, and Öndörshireet-soum-level time series for livestock numbers, herder households, rural household income, Consumer Price Index (CPI), and rural poverty are obtained from publications of the National Statistics Office of Mongolia (NSO), including the NSO Statistical Yearbook and the Household Socioeconomic Survey [15,16]. Real income is deflated to a 2018 base using the NSO CPI series. These series are official aggregates published at the national, aimag, and soum levels. Further disaggregation to the bag or pasture-user group (PUG) level is generally not published; therefore, any PUG- or bag-level allocation from higher administrative units is treated as analytical reconstruction rather than direct observation. Livestock pressure is represented using head counts and Sheep Units (SUs). SUs is used as a standardized measure of livestock pressure based on species-level head counts. Because species coefficients affect the constructed pressure variable, the SU conversion should be interpreted as a standardized analytical measure rather than as an independently observed variable.

Full reproducibility of the livestock-pressure measure would require an accompanying supplementary workflow or data documentation that specifies the Sheep Unit coefficients by species and the rule used to aggregate household-, PUG-, or soum-level head counts. The present manuscript, therefore, reports SU as a constructed analytical input rather than as an independently observed variable.

4.2. Satellite-Derived/Backcast Vegetation Indicators and Reconstructed SOC, AGB, and BGB

Vegetation condition is represented using the Normalized Difference Vegetation Index (NDVI), treated as a satellite-derived/backcast vegetation indicator. NDVI is used as an

indicator of vegetation condition, not as a direct measure of biomass, forage production, soil condition, or ecosystem service delivery. The full 2002–2024 NDVI series should not be interpreted as a Sentinel-2-only record; pre-Sentinel values are treated as backcast analytical values rather than direct Sentinel-2 observations.

A 2024 baseline of soil organic carbon (SOC), above-ground biomass (AGB), and below-ground biomass (BGB) at the bag level is taken from the Mongolian National Bag SOC and Biomass layer (1458 bags), which is derived from Sentinel-2 composites, MODIS GPP indicators, and field validation samples. The Öndörshireet baseline is anchored by 60 SOC field plots analyzed at an ISO/IEC 17025-accredited laboratory [24]. Annual SOC trajectories for 2002–2023 are reconstructed from the 2024 baseline using a satellite-derived/backcast NDVI indicator and RothC-style SOC trajectory assumptions parameterized for Mongolian climate conditions. AGB time series are scaled allometrically to the NDVI backcast, while BGB is derived from AGB using a fixed allometric ratio and a baseline BGB intercept. The reconstructed SOC, AGB, and BGB time series are therefore model-reconstructed variables rather than independently observed annual field measurements. This distinction is central to the interpretation of predictive performance metrics, econometric associations, and scenario-based soil-carbon calculations reported later in the paper. Full reproducibility of the ecological reconstruction would require an accompanying supplementary workflow or data documentation that specifies the pre-Sentinel NDVI backcasting source and procedure, RothC-style parameter values, NDVI-to-AGB scaling, AGB-to-BGB ratio, baseline BGB intercept, and any calibration checks used in the reconstruction. The present manuscript, therefore, reports SOC, AGB, and BGB as constructed analytical inputs rather than as independently observed annual series.

4.3. Climate Controls

Climate controls are drawn from ERA5-Land for annual and seasonal precipitation, mean and seasonal temperature, growing-degree days, and reference evapotranspiration. ERA5-Land is treated as a gridded reanalysis product aggregated to the soum-year and PUG-year levels. The NAMEM Mongolian dzud index represents dzud exposure; the Standardized Precipitation–Evapotranspiration Index at a 12-month scale (SPEI12) is derived from CRU TS; and SMAP provides soil-moisture indicators. Climate variables are aggregated to the soum-year and PUG-year resolution. Resolution mismatches between gridded climate data and administrative or PUG boundaries are a known limitation and are treated as part of measurement uncertainty.

Full reproducibility of the climate controls would require the accompanying supplementary workflow or data documentation to specify the NAMEM dzud-index construction, SPEI12/CRU TS calculation, ERA5-Land variables and aggregation procedure, and SMAP product/version and aggregation procedure. The present manuscript, therefore, reports these climate controls as constructed or aggregated analytical inputs rather than as direct plot-level annual observations.

4.4. Household and PUG Livestock Data

The 2024 Öndörshireet livestock census comprises 514 households across 9 PUGs and includes species-level headcounts. A multi-wave household income panel (2018, 2020, 2022, 2023, 2024; $n = 114$ weighted observations) supplies the income, expenditure, and herd-size series. The waste ratio is constructed from a pilot-area field audit of 320 slaughter events covering hide, wool, offal, blood, bone, fat, and other animal-derived materials. The household sample and the field audit are specific to the Öndörshireet pilot area; generalization to the national soum panel or to other ecological zones is not assumed. Waste-ratio estimates may differ across herd structures, market-access conditions, slaughter

practices, transport costs, and processing capacity, so the audit is interpreted as pilot-area evidence rather than a national parameter.

Full reproducibility of the household and field-audit variables would require an accompanying supplementary workflow or data documentation that specifies the household-panel harmonization procedure, slaughter-event sampling protocol, live-weight basis, by-product categories, and any weighting used in the 320-event audit. The present manuscript, therefore, reports these variables as constructed analytical inputs whose interpretation is limited to the pilot-area data structure.

4.5. Panel Structure and Analytical Units

Two analytical panels are constructed. The PUG panel comprises 9 entities $\times$ 23 years = 207 observations, and the national soum panel comprises 338 soums $\times$ 23 years = 7774 observations. The 23-year window covers 2002–2024 and includes four major dzud cycles (2002, 2010, 2017, 2022). The balanced panels combine observed statistical data, field-observed baseline information, satellite-derived/backcast indicators, and reconstructed ecological trajectories. They should therefore be interpreted as reconstructed analytical panels rather than fully observed longitudinal SOC, AGB, or BGB datasets. This feature is reported explicitly because it directly affects the interpretation of predictive performance and within-entity variability.

4.6. Data Source Table

Table 1 summarizes the main data sources, variables, evidentiary status, spatial level, period, processing, and principal limitations. The table separates observed data from reconstructed variables and scenario-based parameters to avoid implying that all variables are independently observed annual measurements.

Table 1. Data sources, variable construction, and evidentiary status.

Group	Variables	Spatial Level	Period	Processing	Limitation
Livestock	head count, Sheep Unit	National/aimag/soum/PUG	2002–2024 (NSO national series also reported back to 1970)	SU conversion using species coefficients	NSO publishes soum totals; bag/PUG disaggregation is analytical, not observed
Vegetation	NDVI (peak season)	Pixel aggregated to PUG/soum	2002–2024	Growing-season mean; cloud masking; NDVI back-cast for pre-2015 years	NDVI is an indicator, not a direct measure of biomass or productivity; backcast for pre-2015 years
Soil organic carbon	SOC (tC/ha, 0–30 cm)	Plot/PUG/soum	2024 baseline + 2002–2023 reconstruction	RothC-style SOC trajectory + NDVI-linked AGB allometric	Annual SOC values 2002–2023 are model-reconstructed, not independently observed
Biomass	AGB, BGB (kg DM/ha)	PUG/soum	2002–2024 reconstruction	Allometric scaling to NDVI	AGB and BGB are mechanically linked to NDVI; not an independent observation channel
Household income	Real household income (2018 base)	Household/PUG	2002–2024	Deflated by NSO CPI; reindexed to 2018 = 100	Multi-wave panel size is modest; deflator measurement risk; pre-2018 CPI splice
By-product waste	WasteRatio	Slaughter event	2024 ($n = 320$ events)	Non-recovered share of live weight	Pilot area only; not nationally representative

Table 1. Cont.

Group	Variables	Spatial Level	Period	Processing	Limitation
Climate	Precipitation, temperature, dzud, SPEI	Grid aggregated to soum/PUG	2002–2024	Annual and seasonal aggregation	Resolution mismatch between gridded data and admin units

Note. Observed administrative/statistical data, field-observed data, satellite-derived/backcast indicators, model-reconstructed variables, machine-learning outputs, and scenario-based parameters have different evidentiary status. The annual SOC, AGB, and BGB series have been reconstructed and should not be interpreted as independently observed annual field measurements. The full-period NDVI series should not be described as Sentinel-2-only. Scenario parameters are conditional assumptions and do not establish project registration, VM0042 compliance, or credit-issuance readiness.

5. Methodology

This study uses an observational, reconstruction-based, and scenario-based empirical design. The panel datasets should not be interpreted as fully observed longitudinal SOC panels, because annual SOC, above-ground biomass (AGB), and below-ground biomass (BGB) values are model-reconstructed from a 2024 field baseline using satellite-derived/backcast NDVI indicators and RothC-style assumptions. Accordingly, the econometric models estimate conditional associations, the machine-learning models evaluate predictive consistency under stated feature specifications, and the carbon-finance model provides scenario-based sensitivity calculations rather than verified crediting estimates or project-performance forecasts.

The methodological workflow can be summarized as follows: observed administrative and household data, field SOC baseline information, pilot-area slaughter-event audit data, satellite-derived/backcast vegetation indicators, and climate controls are assembled; SOC, AGB, and BGB are reconstructed; fixed-effects and exploratory robustness models are estimated; machine-learning diagnostics are used to assess predictive consistency; and Monte Carlo uncertainty and scenario sensitivity calculations are used to evaluate assumption-dependent carbon-finance outputs. Additional details on the computational environment, random seeds, bootstrap settings, Monte Carlo draws, cross-validation design, and reproducibility documentation are provided in Appendix A.1.

5.1. Panel Regressions: Conditional Associations

Fixed-effects panel regressions are estimated to summarize conditional associations among livestock pressure, vegetation condition, model-reconstructed soil organic carbon, by-product waste, and household income. The main reduced-form income equation is:

$$\ln(\text{Income}_{it}) = \beta_0 + \beta_1 \text{NDVI}_{it} + \beta_2 \ln(\text{SU}_{it}) + \beta_3 \text{WasteRatio}_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where $\ln(\text{Income}_{it})$ denotes the natural logarithm of real household income for entity i in year t ; NDVI_{it} denotes the vegetation-condition indicator; $\ln(\text{SU}_{it})$ denotes the natural logarithm of Sheep Units as a standardized livestock-pressure measure; WasteRatio_{it} denotes the non-recovered or low-value by-product share from the pilot-area field-audit construction; μ_i denotes entity fixed effects; λ_t denotes year fixed effects; and ε_{it} denotes the error term. In the local panel, entities are pasture-user groups (PUGs); in the national panel, entities are soums.

This equation is estimated as a two-way fixed-effects model with PUG-clustered standard errors. The fixed-effects models estimate conditional associations rather than causal effects; they do not identify a closed causal loop. A separate panel model relates model-reconstructed soil organic carbon to grazing pressure, precipitation, temperature, the SU/SOC ratio, and NDVI, conditional on entity fixed effects.

Because the dependent variable in this model is reconstructed SOC, and because some predictors are mechanically related to SOC or NDVI, the SOC model is interpreted as a diagnostic association within a reconstructed panel rather than as independent evidence of observed annual soil-carbon change. Given the small number of PUG clusters (9 entities), conventional cluster-robust inference is fragile. Wild-cluster bootstrap evidence, where available, is treated as supplementary rather than definitive; exact bootstrap p -values are not introduced here unless verified from the analysis files.

5.2. Instrumental-Variable Specification as an Exploratory Robustness Check

An instrumental-variable specification using lagged NDVI as an instrument for contemporaneous NDVI is reported as an exploratory robustness check. The assumed relevance condition is that the lagged vegetation condition is correlated with the current vegetation condition. The assumed exclusion restriction is that lagged NDVI affects current household income only through contemporaneous vegetation conditions, after accounting for fixed effects and controls. The first-stage F-statistic is reported for completeness, but first-stage strength does not address the validity of the exclusion restriction. In this setting, the exclusion restriction cannot be fully verified because lagged vegetation may be correlated with persistent unobserved determinants of household income, including local ecological quality, household adaptive capacity, market access, grazing institutions, herd quality, or repeated climate exposure. The IV-FE specification is therefore not treated as a causal identification result.

5.3. Machine-Learning Predictive Models

Seven supervised regressors are evaluated for predictive performance against model-reconstructed SOC and $\ln(\text{Income})$: histogram-gradient boosting, random forest, gradient boosting, extra trees, ridge, elastic net, and OLS. The ecological prediction target is model-reconstructed SOC, not independently observed annual SOC change. Models are evaluated using a random 70/30 holdout and 5-fold cross-validation for the PUG panel; a soum-grouped 70/30 holdout, 5-fold cross-validation, and an additional 5-fold aimag spatial-block cross-validation for the national panel; and leave-one-year-out validation for temporal robustness. All models use `random_state = 2025`.

Because the SU/SOC ratio includes SOC in its construction, full-specification predictive performance may be inflated when model-reconstructed SOC is the target for prediction. The full-specification results are therefore interpreted as evidence of internal predictive consistency within the reconstructed data structure rather than as independent ecological validation. Leakage-free validation, excluding predictors that inherently contain SOC, would be needed for a more conservative assessment of predictive performance; exact leakage-restricted R^2 , RMSE, or cross-validation values should not be reported unless verified. Permutation importance, based on 30 repeats, is reported as model-based predictor importance and is interpreted as diagnostic feature-ranking evidence rather than causal evidence.

5.4. Monte Carlo Uncertainty Assessment for the Scenario Soil-Carbon Estimate

A 10,000-draw Monte Carlo computation based on the field-plot sampling distribution and a 1000-bootstrap HGB-based uncertainty check are reported as complementary assessments of uncertainty in modeled changes in SOC stock. Because no formal probabilistic model with priors and likelihood is specified, this analysis is described only as a Monte Carlo uncertainty assessment and bootstrap-based uncertainty check.

The metric used is $UNC = 2 \times SD(\Delta SOC) / \text{mean}(\Delta SOC)$.

The 30 percent ceiling cited in the present paper refers to the value used in the scenario calculation under the applicable version of Verra's VM0042 methodology. This calculation

does not constitute validation of the VM0042 methodology, project eligibility, project registration readiness, verified emission reductions, or credit-issuance readiness.

5.5. Scenario Model and Sensitivity Analysis

The scenario model evaluates how alternative assumptions on compliance, leakage, buffer deduction, adjustment factors, carbon price, weighted average cost of capital (WACC), revenue sharing, herd reduction, by-product uplift, and SOC restoration affect modeled net emission reductions and per-household financial outcomes over a 20-year horizon.

The compliance multiplier represents assumed implementation and maintenance of the management conditions required by the scenario; leakage, buffer deduction, and adjustment factors represent conservative scenario deductions; carbon price and WACC represent market and financing assumptions; and revenue sharing represents an assumed benefit-sharing rule rather than an observed payment arrangement.

All financial outputs are scenario-based calculations conditional on stated assumptions; they do not represent verified, audited, or projected estimates of project performance. The scenario analysis is therefore used to evaluate parameter dependence, not to demonstrate VM0042 compliance, verified emission reductions, audited carbon revenue, investment-grade returns, project registration, or credit issuance. The calibration details for the scenario parameters, including UNC, leakage, buffer deduction, adjustment factor, precision factor, compliance multiplier, SOC restoration trajectory, carbon price, and household revenue-share assumptions, are reported in Appendix A.3.

6. Results

6.1. Descriptive Panel

Descriptive panel trends are broadly consistent with the national NSO time series. Over the 23-year window, Mongolia's total livestock count rose from 23.9 million head in 2002 to a peak of around 71.1 million head in 2022 and, according to the 2024 NSO Statistical Yearbook revision, was recorded at 57.6 million head in 2024. Four major dzud cycles are visible in the series: 2002 (Mongolia livestock 23.9 M, with subsequent contractions through 2003), 2010 (32.7 M, down 25.6% from 2009), 2017 (66.2 M after a moderate dzud), and 2022 (71.1 M, followed by a further fall to 57.6 M by 2024). Real rural household income, deflated to 2018 MNT using the NSO CPI, is volatile across the period, with declines coinciding with dzud years. These values are treated as observed administrative and statistical data rather than model outputs.

The satellite-derived/backcast NDVI indicator declines across both panels, and the model-reconstructed SOC time series consequently declines over the same period, as shown in Figure 2, with the Öndörshireet soum-level mean SOC decreasing from 50.24 tC/ha in 2002 to 39.24 tC/ha in 2024. This trajectory should be interpreted as a reconstruction conditional on the backcast rule described in Section 4.2, not as an independently observed annual SOC series.

6.2. Machine-Learning Predictive Performance

Several tree-based models exceed the diagnostic reference line for model-reconstructed SOC under the fitted full specification. On the national soum panel (7774 observations, 338 soums $\times$ 23 years), histogram-gradient boosting attains an out-of-sample R^2 of 0.942 (RMSE = 3.98 tC/ha), followed by gradient boosting (0.927), random forest (0.910), and extra trees (0.889). On the PUG panel (207 observations, 9 PUGs $\times$ 23 years), ExtraTrees attains an out-of-sample R^2 of 0.895 with a 5-fold CV mean of 0.819 ± 0.139 .

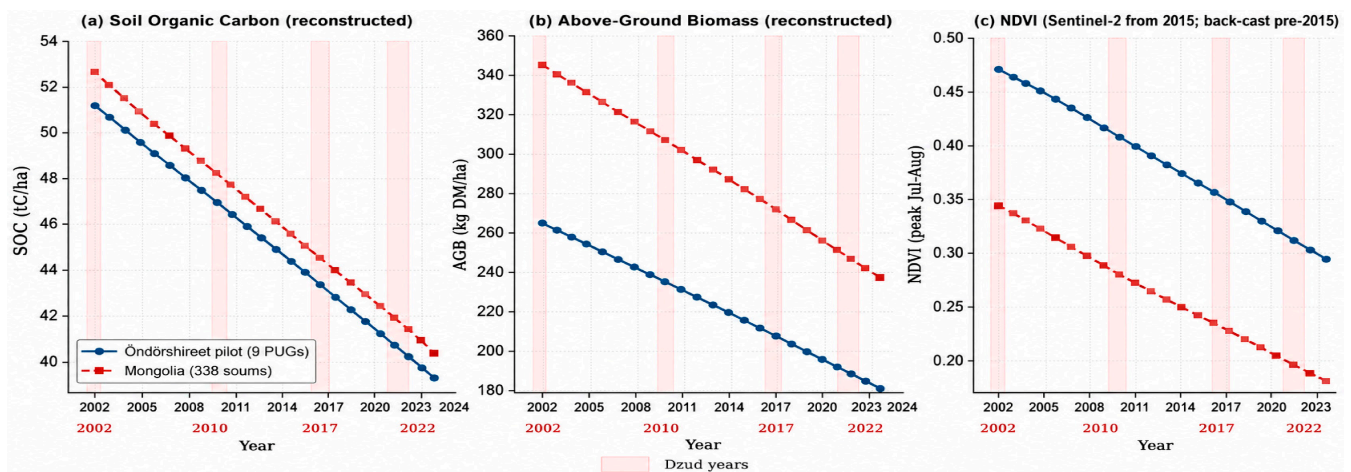


Figure 2. Model-reconstructed ecological trajectories of soil organic carbon, above-ground biomass, and satellite-derived/backcast NDVI, 2002–2024. The SOC and AGB trajectories are conditional on the 2024 field baseline, the satellite-derived/backcast NDVI indicator, and a RothC-style soil-carbon assumption set; they should not be interpreted as independent annual field observations. Pink shading marks dzud years (2002, 2010, 2017, 2022).

These estimates should be read as predictive diagnostics for model-reconstructed SOC under the fitted feature set, not as independent validation of observed annual soil-carbon change. The national-panel R^2 of 0.942, therefore, indicates high internal predictive consistency within the reconstructed SOC panel rather than independent validation of observed annual SOC dynamics. The results are relevant to the scenario assessment, but they do not establish compliance with the methodology or readiness for carbon-credit issuance. Because the SU/SOC ratio mechanically contains SOC, the full-specification predictive results are subject to leakage risk. Leakage-free validation would be needed for a more conservative assessment of predictive performance, and exact leakage-restricted R^2 , RMSE, or cross-validation values are not reported here because verified values are not available in the manuscript file. The predictive performance of the machine-learning models is summarized in Figure 3.

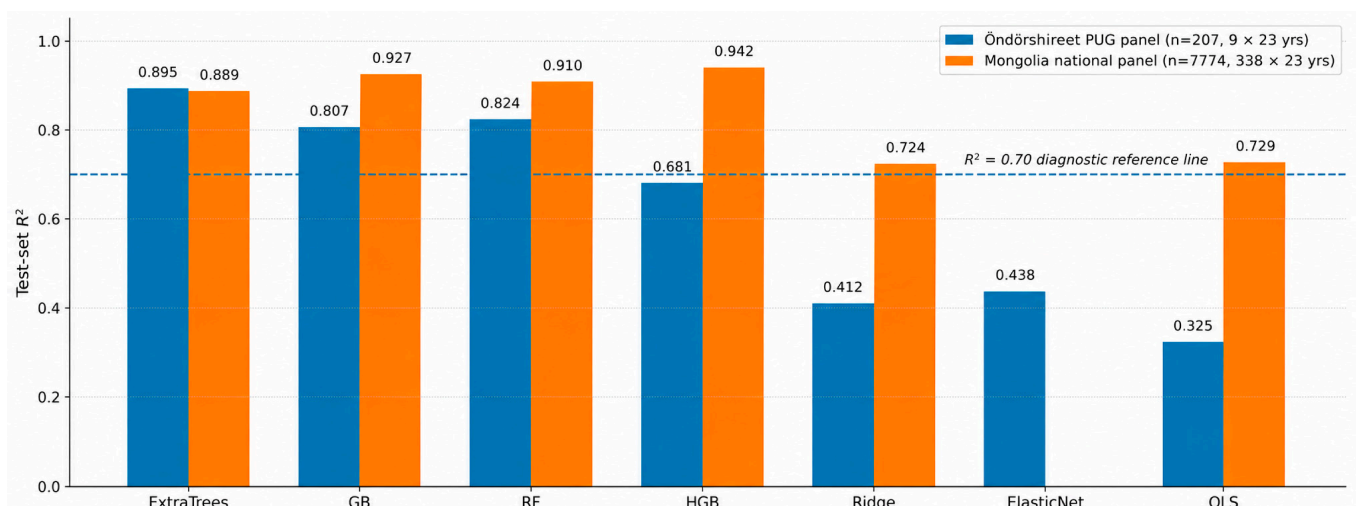


Figure 3. Predictive performance of seven machine-learning models for model-reconstructed SOC across the two panel scales. The dashed line is a diagnostic reference line for visual interpretation only; it is not a methodological benchmark and does not imply compliance with the Verra methodology or independent validation of observed annual SOC change.

Table 2 reports the predictive performance of the seven machine-learning models for model-reconstructed SOC across the PUG and national soum panels. Under the fitted full specification, tree-based models generally outperform linear baselines, with ExtraTrees showing the strongest performance in the PUG panel and histogram-gradient boosting showing the strongest performance in the national soum panel. These results indicate predictive consistency within the reconstructed data structure, but they should not be interpreted as independent validation of observed annual SOC change or as evidence of compliance with the Verra methodology.

Table 2. Predictive performance for model-reconstructed SOC.

Model	PUG R^2 ($n = 207$)	PUG CV-5 R^2	National R^2 ($n = 7774$)	National Spatial CV R^2
HGB	0.681	0.634 ± 0.13	0.942	0.878 ± 0.05
RF	0.824	0.781 ± 0.16	0.910	
GB	0.807	0.797 ± 0.19	0.927	
ExtraTrees	0.895	0.819 ± 0.14	0.889	
Ridge	0.412	-0.339 ± 0.98	0.724	
ElasticNet	0.438	-0.303 ± 0.95		
OLS	0.325	-0.492 ± 1.18	0.729	
Diagnostic reference line ($R^2 = 0.70$)	Exceeds: RF, GB, ET	Exceeds: RF, GB, ET	Exceeds: HGB, GB, RF, ET, Ridge, OLS	Exceeds: HGB (mean)

Note: Values report predictive diagnostics for model-reconstructed SOC under the fitted full specification. Blank cells indicate values not reported in the summarized outputs and should not be filled without verified analysis files. The $R^2 = 0.70$ line is retained only as a diagnostic reference line for visual interpretation and is not a methodological benchmark. Because SU/SOC mechanically contains SOC, leakage-free validation would be needed for a more conservative assessment of predictive performance.

6.3. Permutation Importance

Permutation importance from the histogram-gradient boosting model on the national soum panel ranks the SU/SOC ratio as the most influential model predictor (mean $\Delta R^2 \approx 2.23$), followed by total SU ($\Delta R^2 \approx 0.43$), the dzud-index shock variable ($\Delta R^2 \approx 0.38$), total area ($\Delta R^2 \approx 0.20$), and AGB ($\Delta R^2 \approx 0.17$). The 23-year panel includes multiple dzud periods, allowing the dzud-index shock variable to enter the model with a non-negligible rank of importance. Permutation importance is interpreted here as diagnostic feature-ranking evidence rather than as causal evidence.

Permutation importance is interpreted here as model-based evidence of predictor importance rather than as a causal estimate. The interpretation of the SU/SOC ranking is further limited because SOC is contained in the construction of the SU/SOC ratio. Therefore, the in-model importance of SU/SOC cannot be cleanly attributed to a causal effect of livestock pressure on soil carbon. The diagnostic permutation-importance and Monte Carlo uncertainty results are summarized in Figure 4.

6.4. Panel Econometrics

Table 3 reports the two-way fixed-effects estimates with PUG-clustered standard errors. NDVI is positively associated with $\ln(\text{Income})$ in both the OLS-FE specification (coefficient 22.42, SE 6.23) and the IV-FE robustness specification (coefficient 9.84, SE 1.28). Because NDVI is measured on a 0–1 scale, the coefficient should be interpreted over small changes in vegetation condition rather than as a full-unit effect. The by-product waste ratio is negatively associated with $\ln(\text{Income})$. The waste-ratio evidence is based on the Öndörshireet pilot-area field audit and should not be interpreted as nationally representative evidence.

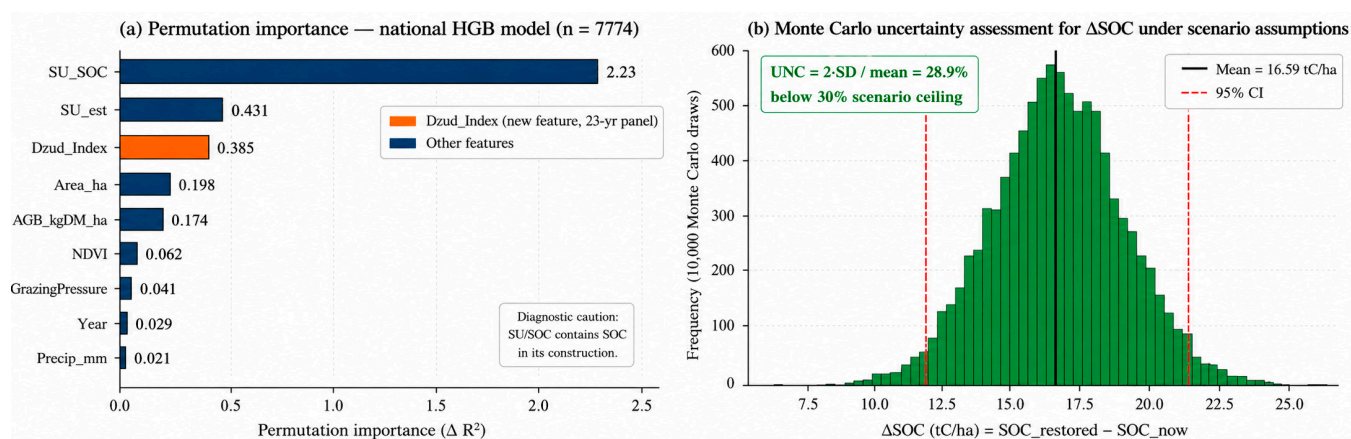


Figure 4. Permutation importance and Monte Carlo uncertainty assessment for scenario-based Δ SOC. Panel (a) reports permutation importance from the fitted national-panel HGB model with 30 repeats. Panel (b) reports the Monte Carlo distribution for Δ SOC under scenario assumptions. Permutation importance is diagnostic model evidence, not causal evidence; the Monte Carlo result is used to assess scenario uncertainty and does not constitute validation of the Verra methodology. The panel is interpreted as a Monte Carlo uncertainty assessment; no formal prior-likelihood model is specified.

Table 3. Fixed-effects estimates for household income.

Variable	OLS-FE	IV-FE (Exploratory Robustness)	Notes
NDVI	22.42 (6.23) ***	9.84 (1.28) ***	$p < 0.001$
ln(SU)	0.384 (0.12) **	0.184 (0.06) **	$p < 0.01$
WasteRatio	−0.84 (0.21) ***	−3.62 (1.48) *	$p < 0.05$
Constant	4.82 (0.98) ***	4.72 (1.12) ***	$p < 0.001$
Within- R^2	0.512	0.531	Two-way FE demeaned residuals
First-stage F		1847	large first-stage statistic; exclusion restriction not verified
N	207	198	23-year panel; lagged-NDVI loses 9 obs
Entity FE	Yes	Yes	
Time FE	Yes	Yes	

Note: Standard errors are reported in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Estimates are conditional associations from fixed-effects specifications and should not be interpreted as causal effects. NDVI is measured on a 0–1 scale, so coefficient magnitudes should be interpreted with caution for small changes in vegetation condition. The IV-FE specification is reported only as an exploratory robustness check because the exclusion restriction on lagged NDVI cannot be fully verified. The PUG panel includes only 9 clusters; therefore, conventional cluster-robust inference is fragile. Wild-cluster bootstrap evidence, where available, is supplementary rather than definitive.

Although the IV-FE first stage is strong ($F = 1847$; above the Stock–Yogo weak-instrument threshold of 10), first-stage strength does not address the validity of the exclusion restriction. Since the exclusion restriction cannot be fully verified, the IV result is reported as exploratory rather than as a causal identification result. The panel SOC determinants model returns the expected signs on grazing pressure and NDVI, and an explicit dzud-index variable enters with a negative coefficient of -8.41 tC/ha per unit (Model 4, within- $R^2 = 0.921$). The high within-panel R^2 is partly mechanical because the SOC backcast embeds NDVI through the AGB allometric relationship.

6.5. Scenario Soil-Carbon Uncertainty

The field-based Monte Carlo computation (10,000 draws) yields a modeled Δ SOC mean of approximately 16.59 tC/ha with a standard deviation of 2.40 tC/ha, corresponding to $UNC \approx 28.9\%$, below the 30 percent ceiling used in the scenario calculation. The HGB-based bootstrap uncertainty check on the 7774-observation national panel yields a substantially smaller UNC of approximately 2.33%, down from the 2.6% estimate from the earlier 2366-observation panel. This lower value reflects the additional information content of the multi-feature ML model relative to a univariate field-mean estimator, but it should be interpreted in light of the SOC panel's reconstructed nature. Both estimates remain below the 30 percent ceiling under the scenario assumptions stated in Section 5.4. This calculation does not constitute validation of the Verra methodology or credit-issuance readiness.

6.6. Scenario Carbon-Finance Outcomes

Under baseline scenario assumptions for the Öndörshireet pilot (262,414 ha; restoration trajectory of 3.05 tCO₂e/ha/yr to close the SOC gap over 20 years; UNC, leakage, buffer, adjustment, and price as specified in Section 5.5), modeled net emission reductions differ materially across compliance scenarios. The four illustrative compliance scenarios—open access (CM = 0.05), conventional PoA (CM = 0.16), integrated governance (CM = 0.50), and theoretical upper bound (CM = 0.65)—produce net reductions and revenue figures that vary substantially with the assumed compliance multiplier. The integrated-governance scenario is treated as one illustrative scenario architecture rather than as a validated, superior, or proven model. The full set of scenario values is reported in Table 4 and illustrated in Figure 5.

Table 4. Scenario-based emission reductions and revenue.

Scenario	CM	Gross Modeled ER (tCO ₂ e/y)	Net Modeled ER (tCO ₂ e/y)	Modeled CCB Revenue (USD/y)	Herder Share at 70% (USD/y)
Open access	0.05	799,648	21,807	\$828,666	\$580,066
Conventional PoA	0.16	799,648	69,784	\$2,651,792	\$1,856,254
Integrated governance	0.50	799,648	218,074	\$8,286,812	\$5,800,768
Theoretical upper bound	0.65	799,648	283,497	\$10,772,886	\$7,541,020

Note: \$ denotes U.S. dollars. Values are scenario-based outputs conditional on the stated assumptions for compliance, uncertainty, leakage, buffer deduction, adjustment, carbon price, and revenue sharing. They do not represent verified emission reductions, audited revenue, VM0042 compliance, project registration readiness, or credit-issuance readiness.

6.7. Household Financial Sensitivity and Feasibility

Per-household financial outcomes vary substantially with baseline income, carbon price, WACC, compliance multiplier, by-product uplift, and revenue-sharing assumptions. Figure 6 shows the modeled household income trajectory and scenario revenue-stack composition under the scenario assumptions. These values are scenario assumptions and not observed project performance estimates.

Table 5 reports the modeled 20-year per-household discounted NPV under three scenario assumptions. The integrated-governance scenario produces a substantially higher modeled NPV than the business-as-usual case, but the magnitude of the uplift is driven in part by the low baseline-income denominator and should be interpreted alongside the sensitivity analysis reported below. These figures are scenario-based financial calculations, contingent on the assumptions in Section 5.5, and do not represent verified financial returns or project-level investment estimates.

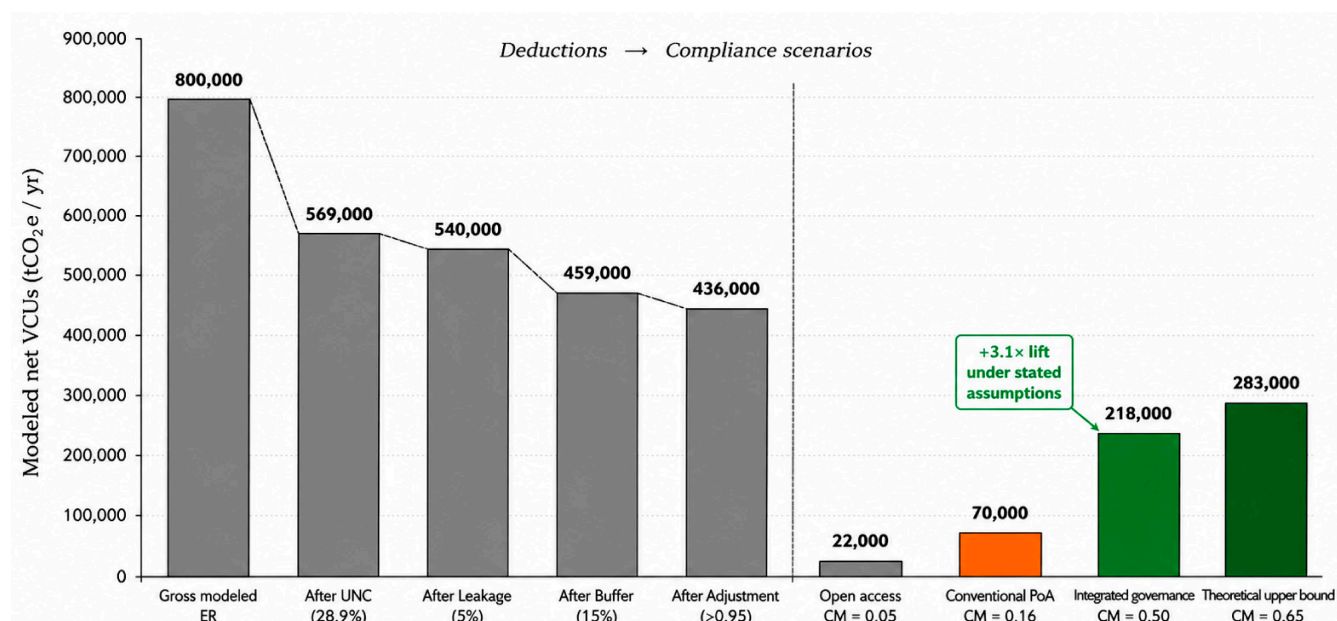


Figure 5. Scenario-based emission-reduction waterfall under the stated assumptions of Section 5.5. The figure shows the deductive chain from gross modeled reductions through UNC, leakage, buffer, and adjustment, followed by four illustrative compliance scenarios. All values are scenario outputs conditional on the stated assumptions and do not represent verified or audited credit issuance. The arrow at the top indicates the transition from deduction stages to compliance scenarios. Table 4 reports the scenario-based net emission reductions and modeled revenue under four illustrative compliance assumptions for the Öndörshireet pilot. Net emission reductions increase from 21,807 tCO₂e/yr under open access to 218,074 tCO₂e/yr under the integrated-governance scenario, indicating that modeled outputs vary substantially with the assumed compliance multiplier. These values are scenario outputs conditional on the assumptions in Section 5.5 and should not be interpreted as verified credit issuance.

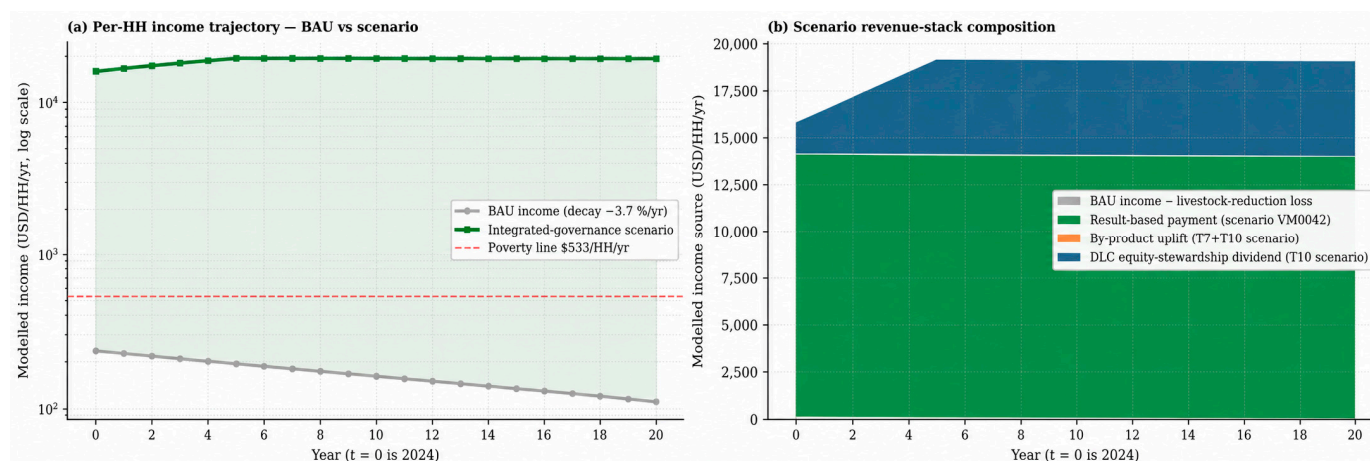


Figure 6. Modeled household income trajectory under scenario assumptions. Panel (a) compares the business-as-usual income trajectory with the integrated-governance scenario relative to the poverty line. Panel (b) shows the composition of the scenario revenue stack, including result-based payments and equity-stewardship dividends. All values are scenario outputs conditional on the assumptions of Section 5.5 and do not represent observed income, guaranteed payments, verified financial returns, or project-level investment estimates.

Table 5. Scenario-based per-household NPV.

Scenario	NPV per HH (USD)	vs BAU	National 100 k HH (USD M)	Annualized Return
BAU	1109		111	n/a
T8 only (no integrated governance)	13,699	+1135%	1370	n/a
Integrated governance	112,201	+10,017%	11,220	25.9%

Note: n/a = not applicable. Values are scenario-based financial calculations over the modeled horizon. They are conditional on scenario assumptions and do not represent verified household income, guaranteed payments, audited financial returns, or investment-grade estimates.

Table 6 summarizes the one-at-a-time sensitivity ranges used to assess how scenario outputs respond to changes in key financial, compliance, and biophysical assumptions. The parameters include carbon price, WACC, compliance multiplier, leakage, buffer deduction, herder revenue share, dividend yield, herd reduction, by-product uplift, and SOC restoration rate. The table is intended to show the range of scenario conditions considered, not to identify a single most likely parameter set.

Table 6. Scenario sensitivity assumptions.

Parameter	Baseline	Low Sensitivity	High Sensitivity	Why This Range Matters
Carbon price (USD/tCO ₂ e)	38	5–10	50	Voluntary-market price volatility
WACC	22%	10–15%	30%	Mongolia country-risk sensitivity
Compliance multiplier (CM)	0.50	0.16	0.65	Main scenario driver
Leakage deduction	5%	15%	30%	VM/project conservativeness
Buffer deduction	15%	25%	40%	Permanence and reversal risk
Herder revenue share	70%	30%	50%	Benefit-sharing sensitivity
Dividend yield assumption	5%	0%	2%	Equity-stewardship assumption risk
Herd reduction toward carrying capacity	85.5%	50%	70%	Ecological feasibility and livelihood shock
By-product uplift	Baseline	0%	+50%	Value-chain uncertainty
SOC restoration rate (tCO ₂ e/ha/yr)	3.05	−50%	+25%	Biophysical uncertainty

Note: The sensitivity ranges are scenario assumptions, not observed parameter estimates. They are used to assess the dependence of modeled outputs on parameters.

7. Discussion

7.1. Evidence Consistent with a Reinforcing Feedback Pattern

Taken together, the fixed-effects estimates, machine-learning diagnostics, Monte Carlo uncertainty assessment, and scenario analysis are consistent with associations among vegetation condition, model-reconstructed soil organic carbon, by-product recovery, and household income. NDVI is positively associated with ln(household income), conditional on entity and time fixed effects, while the by-product waste ratio is negatively associated with ln(income). The fitted machine-learning model also identifies the SU/SOC ratio as an

influential predictor of model-reconstructed SOC, but this diagnostic result should be interpreted with caution because SOC is mechanically embedded in the SU/SOC ratio, and the SOC series itself is reconstructed in part from vegetation-linked assumptions. Accordingly, the full-specification predictive results are best interpreted as internal predictive consistency within a reconstructed data structure, not as independent validation of observed annual SOC change.

These patterns are consistent with a possible reinforcing mechanism whereby ecological stress and economic inefficiency interact under specific institutional and climatic conditions. A plausible interpretation is that vegetation condition affects household income through forage availability, livestock condition, product quality, and the recoverable value of livestock products and by-products. The multi-year decline in vegetation indicators and the associated decline in model-reconstructed soil organic carbon point to a potential loss of ecosystem-service functions, including forage provision, soil carbon storage, and rangeland productivity, contingent on the study's reconstruction assumptions. By-product non-recovery may further weaken the economic return per animal and can create a feedback-loop loss if households respond to low realized value by relying more heavily on herd numbers rather than productivity, quality improvement, or value-added recovery. The evidence, however, remains associational and model-based. It does not establish a closed causal loop, and individual coefficients should be interpreted in light of the methodological cautions discussed in Sections 5 and 6.

7.2. Ecosystem Services, Restoration Relevance, and Transferability Limits

The results are relevant to ecosystem-service discussions because rangeland condition affects not only livestock production but also forage availability, soil organic carbon storage, biodiversity habitat, soil stability, and the capacity of pastoral landscapes to buffer climatic stress. The study does not directly measure all of these ecosystem services; instead, it uses vegetation indicators, model-reconstructed SOC, household income, and by-product recovery as linked empirical and scenario-based indicators. This distinction is important because a decline in NDVI or reconstructed SOC should not be treated as a definitive measure of ecosystem degradation, even though it is consistent with pressure on ecosystem service delivery.

The findings also suggest that restoration or conservation interventions would need to address both ecological and economic constraints. Grazing management, pasture-user-group coordination, monitoring, livestock quality improvement, and by-product recovery may be complementary rather than substitutable interventions, but their effectiveness would depend on the local ecological zone, institutional capacity, market access, and household incentives. Agroforestry, shelterbelt, riparian restoration, reseeding, rotational grazing, resting of degraded pastures, and other restoration practices may be relevant in selected Mongolian contexts, but they should not be assumed to be universally appropriate across steppe, forest-steppe, desert-steppe, and mountain rangelands. The Öndörshireet pilot-area evidence, therefore, should not be generalized mechanically to all Mongolian rangelands without multi-site validation across ecological zones and governance settings.

7.3. Governance and Compliance Assumptions as Scenario-Sensitive Constraints

The scenario analysis shows that the same modeled biophysical restoration capacity produces materially different modeled emission-reduction and revenue outcomes depending on the assumed compliance multiplier. Under baseline assumptions, scenario outputs vary substantially with compliance, carbon price, leakage, buffer deduction, adjustment factors, and revenue-sharing parameters. This finding is consistent with the broader PES

and result-based-payment literature, in which monitoring credibility, payment continuity, opportunity costs, and design parameters strongly influence outcomes [19,21,22].

The scenario-based finding should not be read as a general claim that institutional design dominates biophysical conditions. Rather, it shows that, under the present model setup, alternative assumptions about compliance, monitoring, and benefit sharing materially shift the modeled outputs. In this sense, compliance is treated as a scenario-sensitive constraint rather than as an empirically validated behavioral parameter. The Nomadic Industrial Cluster System is therefore discussed only as one illustrative governance architecture that combines monitoring, incentives, value-chain recovery, and benefit sharing; it is not presented as a validated, superior, or generally transferable model. Alternative governance arrangements, including strengthened pasture-user-group rules, public extension programs, cooperative value-chain models, or hybrid public–private monitoring systems, could also be compatible with the paper’s analytical logic.

7.4. Financial Feasibility Under Scenario Assumptions

The financial figures reported here are scenario-based calculations under restrictive assumptions, not investment-grade estimates, audited revenues, verified project returns, or evidence of project registration or readiness for credit issuance. The 20-year modeled per-household NPV under the integrated-governance scenario is USD 112,201 versus USD 1109 under business-as-usual at a 22 percent WACC; the resulting uplift ratio is mechanically very high, at about $100\times$. This uplift ratio mainly reflects the low baseline-income denominator and should be interpreted alongside the sensitivity analysis in Table 6. The coverage ratio between modeled scenario revenue and modeled livestock-reduction income loss is similarly large under baseline assumptions, but it varies substantially with carbon price, herder share, dividend yield, herd reduction, and other scenario parameters. Under more conservative assumptions, the modeled coverage ratio remains positive across the reported scenario grid; however, this result is conditional on those assumptions and should not be interpreted as a verified financial return or as evidence of project readiness. The financial interpretation is therefore limited to scenario sensitivity: it indicates which assumptions drive feasibility within the model, not whether the proposed project would actually deliver those outcomes under implementation conditions.

7.5. Limitations and Future Validation

Several limitations should be considered before using the findings for project registration, credit-issuance claims, operational decision-making, or transfer to other Mongolian rangeland settings. The key limitations and remaining risks are summarized in Table 7. The outstanding validation steps required before any project-registration, credit-issuance, or operational decision-making claim are summarized in Appendix A.4.

Table 7. Key limitations and remaining risks.

Limitation	Why It Matters	How the Paper Addresses It	Remaining Risk
Single pilot area (Öndörshireet)	Generalisability is limited	National soum panel used for broader contextual calibration; pilot-area results clearly labeled	Local mechanisms may not transfer across ecological zones or governance settings
9 PUG clusters	Conventional cluster-robust inference is fragile in small-cluster settings	Small-cluster caveat reported, and coefficient interpretation kept cautious	Small-sample inference remains fragile

Table 7. *Cont.*

Limitation	Why It Matters	How the Paper Addresses It	Remaining Risk
Reconstructed SOC trajectory	Annual SOC values for 2002–2023 are not independently observed	Field baseline plus NDVI/RothC-style backcast clearly labeled as reconstruction	High predictive R^2 may partly reflect construction logic
SU/SOC ratio and ML leakage risk	SOC appears mechanically in the SU/SOC predictor	Full-specification results interpreted as diagnostic; leakage-free validation identified as necessary	Full-model importance may overstate the role of SU/SOC
Lagged-NDVI instrument	Exclusion restriction cannot be fully verified	IV-FE is treated as an exploratory robustness check only	IV result is not interpreted as a causal effect
WasteRatio field audit	Pilot-specific 320-event evidence is not nationally representative	Clearly labeled as pilot-area field-audit evidence	Channel needs multi-site replication
Illustrative governance architecture	Scenario architecture may raise advocacy or transferability concerns	NICS is framed as an illustrative scenario architecture, not a validated solution	Alternative governance arrangements require empirical comparison
VM0042 version and project eligibility	Methodology requirements can change, and project-specific eligibility must be validated independently	Wording limited to scenario framing and methodological reference	Compliance, validation, registration, and credit issuance are not demonstrated

8. Conclusions

First, the present analysis is consistent with the proposed ecological–economic feedback framework in Mongolian rangelands, while remaining associational and reconstruction-dependent. Across the dual-scale panel, NDVI is positively associated with $\ln(\text{household income})$, the by-product waste ratio is negatively associated with $\ln(\text{income})$, and tree-based machine-learning models show high internal predictive consistency for model-reconstructed soil organic carbon under the fitted specification. These results suggest a reinforcing association among livestock pressure, vegetation condition, model-reconstructed soil-carbon dynamics, by-product recovery, and household income, but they do not establish a closed causal loop or independently observed annual SOC change. The permutation-importance results should be read as model-based diagnostic evidence only, and the ranking of the SU/SOC ratio is qualified by the fact that SOC enters the predictor mechanically. Second, the scenario analysis shows that carbon-finance outcomes are highly sensitive to assumptions about compliance, carbon price, weighted average cost of capital, leakage, buffer deduction, herder revenue share, dividend yield, herd-reduction parameters, and by-product value recovery. The modeled outputs, therefore, illustrate how assumptions about governance, monitoring, benefit sharing, and participation can affect scenario-based outcomes; they do not represent verified emission reductions, audited revenues, investment-grade returns, project-registration readiness, or credit-issuance readiness. The financial and household-level results require recalibration using observed data on compliance, participation, monitoring, payments, and local implementation costs. Third, the policy implication is that rangeland carbon-finance mechanisms in pastoral systems should be evaluated as combined ecosystem-service, livelihood, governance, and measurement interventions rather than as carbon-accounting exercises alone. The Nomadic

Industrial Cluster System is treated here as one illustrative scenario architecture among possible governance arrangements; its operational feasibility, distributional effects, and compliance performance require independent empirical validation and transparent disclosure of conflicts of interest. Fourth, future research should prioritize independent multi-site validation across Mongolia's ecological zones, leakage-free machine-learning specifications that exclude predictors mechanically containing the response variable, repeated stratified soil sampling, and direct observation of compliance, participation, monitoring, and payment processes. Any project registration, VM0042 eligibility assessment, verified emission-reduction claim, or credit-issuance claim would require independent validation under the applicable methodology and should not be inferred from the present associational, reconstruction-dependent, and scenario-based analysis.

Author Contributions: Conceptualization, E.D.; methodology, E.D., T.S. and M.D.; software, S.B.; validation, E.D., T.S. and S.B. and M.D.; formal analysis, E.D., E.E. and S.B.; resources, E.E. and U.M.; data curation, T.S. and U.M.; writing—original draft, E.D. and T.S.; writing—review and editing, T.S., S.B. and M.D.; visualization, T.S., E.E. and U.M.; project administration, E.D.; funding acquisition, E.D., S.B. and U.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external public, charitable, or government funding. Analytical work was carried out at NICS LLC.

Institutional Review Board Statement: Ethical review and approval were waived for this study, as it is based on anonymized survey data and does not involve sensitive personal information or clinical interventions, in accordance with institutional research guidelines.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Aggregated panel data, ML model outputs, sensitivity grids, and the scenario cash-flow model are provided in the companion Excel workbook (NICS_70_70_VVB_Q1_Consolidated.xlsx). The structure and contents of the companion Excel workbook are summarized in Appendix A.5. Disaggregated household-survey records, the 320-event field audit, and the SHUUKH ISO/IEC 17025 raw soil reports are available from the corresponding author, subject to data-sharing agreements with the National Statistics Office of Mongolia, Töv Aimag administration, and SHUUKH Soil and Water Laboratory. NSO publications cited in this study are publicly available at www.1212.mn (accessed on 5 May 2026).

Conflicts of Interest: E.D. is the inventor of a Mongolian patent (Patent 10-0005244) covering the proposed scenario architecture referred to in this paper as the Nomadic Industrial Cluster System, and a principal of NICS LLC. T.S. has no financial relationship with NICS LLC beyond co-authorship of the present manuscript. The authors disclose that E.D. has an affiliation with NICS LLC as a potential conflict of interest. The empirical analysis is based on ISO/IEC 17025-accredited laboratory measurements, publicly available NSO statistics, publicly available satellite imagery, and a pilot-area field audit. The Nomadic Industrial Cluster System is treated in this paper as a proposed scenario architecture rather than a validated solution; this paper does not constitute a Verra methodology validation.

Appendix A

Appendix A.1. Reproducibility Statement

All Python code, random seeds, and intermediate data artifacts are documented in the companion Excel workbook (sheet 22_Audit_Trail). The current build uses the extended 23-year panel for 2002–2024, comprising 207 PUG-year observations and 7774 soum-year observations. This replaces the earlier 7-year build, which contained 63 PUG-year and 2366 soum-year observations. The computational stack is Python 3.12, scikit-learn 1.8.0, statsmodels 0.14.6, and linearmodels 7.0. Randomization uses `numpy.random.default_rng` (2025) and `sklearn.random_state = 2025`. Bootstrap procedures use 1000 iterations for the

R^2 confidence interval and the HGB bootstrap-based uncertainty check. The Monte Carlo computation uses 10,000 draws to estimate the uncertainty in soil carbon. Cross-validation includes random 5-fold KFold and a 70/30 holdout for the PUG panel, where the small number of entities makes GroupKFold overly restrictive; GroupKFold by Soum with 5 folds for the national panel; and an additional 5-fold aimag spatial-block cross-validation on the national panel as a check for spatial leakage, with a mean R^2 of 0.878.

Appendix A.2. Variable Construction Map

The variable construction framework is summarized as $f(y) = g(x_1, x_2, z, p, m, h, c)$. Outcomes y include $\ln(\text{household income})$, waste ratio, and scenario-based carbon-finance outcomes. Livestock variables x_1 include Sheep Units (SU), species-level head counts, meat biomass, and waste ratio. Ecological variables x_2 include SOC (tC/ha), above-ground biomass (AGB, kg DM/ha), below-ground biomass (BGB, kg DM/ha), and NDVI. Climate variables z include precipitation, temperature, growing-degree days, SPEI12, snow depth, dzud index, SMAP soil moisture, and evapotranspiration. Price variables p include meat, hide, wool, cashmere, milk, offal, and CPI. Management variables m include rotation, seasonal rest, and cooperative membership. The cognition variable h refers to the NICS five-stage construct and is used only as a narrative framing device. Scenario carbon parameters c include UNC, leakage, buffer, adjustment factor, precision factor, FLU, FMG, FI, CM, and permanence.

Appendix A.3. Scenario Parameter Calibration

The field-based scenario uncertainty estimate is $\text{UNC} = 28.9\%$, based on a 10,000-draw Monte Carlo computation using the field-plot sampling distribution. The HGB bootstrap-based uncertainty check is $\text{UNC} = 2.33\%$, based on 1,000 bootstrap iterations on the training set from the 7774-observation national panel. Both estimates remain below the 30 percent ceiling used in the scenario calculation under the applicable VM0042 version. The scenario assumptions are as follows: leakage = 5%; buffer = 15%; adjustment factor = 0.95; and precision factor $(1 - \text{UNC}) = 0.711$. The compliance-multiplier trajectory moves from 0.16 to 0.50 via $\delta^* = 0.14$, with a logistic ceiling of 0.65. The dzud-index coefficient in Model 4 is -8.41 tC/ha per unit, indicating that dzud shocks temporarily reduce effective CM by approximately 0.05–0.08 in dzud years. The SOC restoration trajectory is 3.05 tCO₂e/ha/yr over the 20-year scenario horizon. The carbon price is set at USD 38/tCO₂e under CCB Gold-tier scenario assumptions. The herder's revenue share is 70%. The result-based payment per household is USD 13,911 per year, calculated as $\text{net VCU} \times \text{USD } 38 \times 70\% \div 417$ households; this updates the earlier 7-year model estimate of USD 12,590. All parameters are scenario assumptions and require recalibration against observed compliance, participation, monitoring, and payment data before project registration, credit-issuance claims, or operational decision-making.

Appendix A.4. Outstanding Validation Steps

Three external validation steps are identified before any project registration or credit-issuance claim can be supported. First, full operational compliance and participation data should be collected for all participating households over at least one annual cycle. Second, the proposed value-chain Phase-A development underlying the equity-stewardship assumption should be implemented and documented. Third, a second stratified soil-sampling campaign with at least 60 plots should be conducted to reduce the risk of site transfer relative to a reference exclosure benchmark. Until these steps are completed, the present manuscript should be read as an empirical, scenario-based assessment rather than as a Verra submission monitoring report. It does not establish methodology compliance.

Appendix A.5. Companion Data File

The companion file, NICS_70_70_VVB_Q1_Consolidated.xlsx, contains 37 sheets. It includes the extended dual-scale panel data with 207 PUG-year and 7774 soum-year observations for 2002–2024; NSO national time-series for 1970–2025; soum-level livestock-by-Sheep-Unit series for all Mongolian soums; machine-learning model outputs; panel regression tables; Monte Carlo uncertainty results; scenario VCU outputs; the dynamic cash-flow waterfall; the sensitivity grid; the reference bibliography; and the audit trail. Sheet 00_README contains the full sheet directory.

References

1. Reynolds, J.F.; Smith, D.M.S.; Lambin, E.F.; Turner, B.L.; Mortimore, M.; Batterbury, S.P.; Downing, T.E.; Dowlatabadi, H.; Fernández, R.J.; Herrick, J.E.; et al. Global desertification: Building a science for dryland development. *Science* **2007**, *316*, 847–851. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Maestre, F.T.; Le Bagousse-Pinguet, Y.; Delgado-Baquerizo, M.; Eldridge, D.J.; Saiz, H.; Berdugo, M.; Gozalo, B.; Ochoa, V.; Guirado, E.; García-Gómez, M.; et al. Grazing and ecosystem service delivery in global drylands. *Science* **2022**, *378*, 915–920. [\[CrossRef\]](#)
3. Sainnemekh, S.; Barrio, I.C.; Densambuu, B.; Bestelmeyer, B.; Aradóttir, Á.L. Rangeland degradation in Mongolia: A systematic review of the evidence. *J. Arid. Environ.* **2022**, *196*, 104654. [\[CrossRef\]](#)
4. Addison, J.; Friedel, M.; Brown, C.; Davies, J.; Waldron, S. A critical review of degradation assumptions applied to Mongolia's Gobi Desert. *Rangel. J.* **2012**, *34*, 125–137. [\[CrossRef\]](#)
5. Jamsranjav, C.; Reid, R.S.; Fernández-Giménez, M.E.; Tsevelee, A.; Yadamsuren, B.; Heiner, M. Applying a dryland degradation framework for rangelands: The case of Mongolia. *Ecol. Appl.* **2018**, *28*, 622–642. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Purevjav, A.O.; Avirmed, T.; Wilcox, S.W.; Barrett, C.B. Climate rather than overgrazing explains most rangeland primary productivity change in Mongolia. *Science* **2025**, *389*, 1229–1233. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Narmandakh, D.; Sakurai, T. Impact of Rangeland Degradation on Farm Performance and Household Welfare in the Case of Mongolia. *Jpn. J. Agric. Econ.* **2022**, *24*, 52–57. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Fernández-Giménez, M.E.; Batkhishig, B.; Batbuyan, B. Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia. *Glob. Environ. Change* **2012**, *22*, 836–851. [\[CrossRef\]](#)
9. Ulambayar, T.; Fernández-Giménez, M.E. How community-based rangeland management achieves positive social outcomes in Mongolia: A moderated mediation analysis. *Land Use Policy* **2019**, *82*, 93–104. [\[CrossRef\]](#)
10. Allington, G.R.; Fernández-Giménez, M.E.; Reid, R.; Ulambayar, T.; Angerer, J.; Jamsranjav, C.; Baival, B.; Batjav, B. Context matters: Rethinking resource governance theories for Mongolian pastoral systems. *Land Use Policy* **2024**, *142*, 107170. [\[CrossRef\]](#)
11. Pettorelli, N.; Vik, J.O.; Mysterud, A.; Gaillard, J.M.; Tucker, C.J.; Stenseth, N.C. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends Ecol. Evol.* **2005**, *20*, 503–510. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action*; Cambridge University Press: Cambridge, UK, 1990.
13. Cox, M.; Arnold, G.; Tomás, S.V. A Review of Design Principles for Community-Based Natural Resource Management. *Ecol. Soc.* **2010**, *15*, 38. [\[CrossRef\]](#)
14. Verra. VM0042 *Improved Agricultural Land Management Methodology*, Version 2.2; Verra: Washington, DC, USA, 2025.
15. NSO. *Household Socio-Economic Survey 2024*; National Statistics Office of Mongolia: Ulaanbaatar, Mongolia, 2024.
16. NSO. *Mongolian Statistical Yearbook 2024*; National Statistics Office of Mongolia: Ulaanbaatar, Mongolia, 2024.
17. Davaatseren, E.; Sodnomdavaa, T.; Enkhbayar, E.; Bayarsaikhan, S.; Mandakh, U. Rangeland Degradation, Vegetation Dynamics, and Household Income in a Mongolian Pastoral System: Panel Evidence from Öndörshireet Soum. *Land* **2026**, *15*, 954. [\[CrossRef\]](#)
18. Li, C.; Fu, B.; Wang, S.; Stringer, L.C.; Zhou, W.; Ren, Z.; Hu, M.; Zhang, Y.; Rodriguez-Caballero, E.; Weber, B.; et al. Climate-driven ecological thresholds in China's drylands modulated by grazing. *Nat. Sustain.* **2023**, *6*, 1363–1372. [\[CrossRef\]](#)
19. Wunder, S.; Brouwer, R.; Engel, S.; Ezzine-de-Blas, D.; Muradian, R.; Pascual, U.; Pinto, R. From principles to practice in paying for nature's services. *Nat. Sustain.* **2018**, *1*, 145–150. [\[CrossRef\]](#)
20. Jayachandran, S.; De Laat, J.; Lambin, E.F.; Stanton, C.Y.; Audy, R.; Thomas, N.E. Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science* **2017**, *357*, 267–273. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Hayes, T.; Murtinho, F.; Wolff, H.; López-Sandoval, M.F.; Salazar, J. Effectiveness of payment for ecosystem services after loss and uncertainty of compensation. *Nat. Sustain.* **2022**, *5*, 81–88. [\[CrossRef\]](#)
22. Izquierdo-Tort, S.; Jayachandran, S.; Saavedra, S. Redesigning payments for ecosystem services to increase cost-effectiveness. *Nat. Commun.* **2024**, *15*, 9252. [\[CrossRef\]](#) [\[PubMed\]](#)

23. Verra. *VM0042 Update: Verra Publishes Minor Revisions to IALM Methodology*; Verra: Washington, DC, USA, 2025. Available online: <https://verra.org/vm0042-update-verra-publishes-minor-revisions-to-ialm-methodology/> (accessed on 3 May 2026).
24. *ISO/IEC 17025:2017*; General Requirements for the Competence of Testing and Calibration Laboratories. International Organization for Standardization: Geneva, Switzerland, 2017.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.