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- Min Liu, State Key Laboratory of Herbage Seeds and Grassland Agro-ecosystems, College of pastoral agriculture science and technology, Lanzhou University, Lanzhou, 730070, China. minliu@lzu.edu.cn
- Wenli Xu, School of Economics, Anhui University, China. xuweny87@hotmail.com
- Hangyu Zhang, China Centre for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, China. hangyuzhang@stu.pku.edu.cn
- Huang Chen, Paula and Gregory Chow Institute for Studies in Economics, Department of Economics, School of Economics, Xiamen University, China. hchen.econ@xmu.edu.cn
- Qiang Bie, Faculty of Geomatics, Lanzhou Jiaotong University, Lanzhou, 730070, China. bieq@lzjtu.edu.cn
- Guodong Han, College of Grassland, Resources and Environment/Key Laboratory of Grassland Resources of the Ministry of Education, Inner Mongolia Agricultural University, Hohhot, 010011, China, hanguodong@imau.edu.cn
- Xiaohua Yu, Department of Agricultural Economics and Rural Development, University of Goettingen, Goettingen, 37073, Germany. xyu@uni-goettingen.de

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Livestock production, greenhouse gases, air pollution, and grassland conservation: Evidence from a quasi-natural experiment

ABSTRACT

Serious climate challenges and environmental concerns have led to calls to mitigate greenhouse effects and pollution by controlling livestock production. In this study, we performed a cross-boundary quasi-natural experimental analysis of the Mongolian Plateau to examine the causal effects of livestock reduction on greenhouse gas (GHG) emissions and air pollutants. Aimed at grassland conservation by controlling overgrazing, China's grassland ecological compensation policy (GECP) unintendedly offered the opportunity to estimate the causal effects of livestock reduction. To this end, we used official statistical data, remote sensing data, reanalysis data, and household survey data. Empirical findings based on the synthetic difference-in-differences (SDID) approach showed that with the implementation of the GECP, livestock reduction reduced atmospheric GHG and air pollutant concentrations and increased grassland quality and carbon sequestration in grasslands. We extended the basic SDID to the dynamic SDID and used it to estimate the causal effects in each policy year, which presented that the policy effects were more pronounced after several years of continuous implementation. The pathway analysis revealed that atmospheric CH_4 concentrations decreased with the reduction in animal CH_4 emissions and that the $PM_{2.5}$ and PM_{10} concentrations decreased with grassland restoration. These findings provided empirical references for reforming the global food system to ensure both food security and environmental protection.

Keywords:
Greenhouse gases
Air pollutants
Livestock
Synthetic difference-in-differences
Grassland

1. Introduction

Serious climate challenges have led to calls from international agencies, campaign groups, governments, and the media to drastically reduce the global consumption of livestock products based on the assertion that livestock produces considerable greenhouse gas (GHG) emissions (Steinfeld et al., 2006; Houzer and Scoones, 2021). GHG emissions from the livestock industry have been estimated to account for 15%–18% of total anthropogenic GHG emissions (Bellarby et al., 2013; Houzer and Scoones, 2021). According to a life cycle analysis, the total emissions from livestock production ranged from 5.6 to 7.5 Gt of CO_2 equivalent per year over the period 1995–2005 (Herrero et al., 2016). Food system emissions amounted to 17.318 ± 1.675 Gt of CO_2 equivalent in circa 2010, representing 34% of total GHG emissions, 57% of which were attributable to livestock production (Crippa et al., 2021; Xu et al., 2021). Global food system emissions may result in failure to achieve the Paris Agreement target of limiting the global temperature increase to 1.5–2°C above preindustrial levels (Clark et al., 2020).

Emissions from livestock include methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), and ammonia (NH_3). CH_4 and N_2O have considerably more powerful greenhouse effects than CO_2 (Prather and Hsu, 2010; Cooper et al., 2022). Livestock production also contributes to air pollution, such as nitrogen pollution (Bai et al., 2022). High atmospheric NH_3 and nitrogen oxide concentrations lead to the formation of ozone and particulate matter (PM), resulting in detrimental health effects (Bodirsky et al., 2014). CH_4, N_2O, and NH_3 levels have been rising dangerously fast. In 2020, CH_4 and N_2O reached 262% and 123% of preindustrial levels, respectively (Tollefson, 2022). The livestock industry is responsible for 33% of global CH_4 emissions and 66% of agricultural CH_4 emissions (Houzer and Scoones, 2021). In China, the rising demand for meat and animal feed increased NH_3 emissions from agriculture by 63% and annual $PM_{2.5}$ levels by up to 10 $\mu g/m^3$ over the period 1980–2010 (Liu, Tai, et al., 2021).

Given these environmental effects, reducing the consumption of livestock products, promoting protein transition to vegan diets, and producing plant-based or industrially manufactured alternatives have been embraced to reduce GHG emissions and air pollutants (Gerber et al., 2013; Goodland, 2013; Pérez-Domínguez et al., 2021; Van Selm et al., 2022). GHG taxes on animal food products in the EU and burping taxes on cows and sheep in New Zealand have been implemented to reduce GHG emissions from livestock production (Wirsenius et al., 2011). To reduce the EU's food-related carbon footprint by 50%, it has been suggested that the consumption of meat, milk, and other dairy products needs to be reduced by 79%, 74%, and 83%, respectively (Bellarby et al., 2013; Westhoek et al., 2014). The 50by40 initiative, launched by an alliance of organizations around the world, aims to halve animal consumption by 2040. All these measures and programs aim to mitigate greenhouse effects and air pollution by reducing and shifting livestock production.

However, the Food and Agriculture Organization estimates that by 2050, the global demand for meat and milk will double compared to that at the beginning of the 21st century, with the increase coming mostly from developing countries (FAOUN, 2009). Concerns about reducing GHGs by controlling livestock production in developing countries are extremely difficult to address while the increasing demand remains a pressing problem.

Given the contradiction between calls to reduce GHG emissions and air pollutants from livestock production and safeguarding animal-sourced food security, it is imperative to gain a deeper understanding of the mechanism by which livestock reduction mitigates greenhouse effects and air pollution, which can have profound policy implications for reforming the global food system to ensure both food security and environmental protection. However, to our knowledge, there are no empirical estimates of how GHGs and air pollutants change with livestock reduction. Although gas emissions from animals can be measured, the causal effects of livestock reduction on abating atmospheric GHGs and air pollutant concentrations are not easy to estimate, given the complex photochemical reactions of gases in the atmosphere (Lelieveld and Crutzen, 1992; Prather and Hsu, 2010). The Intergovernmental Panel on Climate Change (IPCC) introduced emission factors to estimate animal gas emissions based on livestock populations (IPCC, 2021), and animal science researchers have employed respiratory chambers, SF_6 tracer gas techniques, and mass balance methods to accurately calculate emissions from animals (Jia et al., 2022). Nevertheless, studies on atmospheric GHGs and air pollutant concentrations determined by livestock production are scarce. Therefore, this study aimed to examine the causal effects of livestock reduction on reducing atmospheric GHGs and air pollutants based on a policy intervention in China that was not intended to reduce GHGs and air pollution.

In 2011, China introduced the grassland ecological compensation policy (GECP), one of the largest payment-for-ecosystem services programs in the world (Hou et al., 2021), to achieve a large-scale and long-term reduction in grazing livestock in pastural areas for the sake of protecting grassland ecosystems. It was believed that overgrazing, a widespread problem in pastural areas in China, caused grassland degradation (Liu et al., 2018; Maestre et al., 2022). The GECP has now been implemented in all permanent grassland areas of China, covering about 6% of the global grassland and involving more than 12 million rural households (NFGA, 2021). Three rounds of the GECP have been implemented since 2011. In the first round (2011–2015), the central government invested RMB 77.4 billion (more than USD 10 billion) in eight typical pastural provinces. In the second round (2016–2020), RMB 93.8 billion (approximately USD 15 billion) was invested. Atypical grasslands in five other provinces have also been covered since the second round. The third round started in 2021 and is ongoing.

The GECP offered the opportunity to assess the effects of livestock reduction on mitigating GHG emissions and air pollutants, although this was not its original intent and has been overlooked by both scholars and policymakers. We performed a quasi-natural experimental analysis to examine the causal effects of livestock reduction with the implementation of GECP on controlling GHGs and air pollutants, as well as grassland restoration. However, the simultaneous nationwide implementation of the GECP in all pastural areas means that its causal effects cannot be clearly identified based on any control areas within China. Thus, we used Mongolia, a country located in eastern Central Asia, as the control area and China's Inner Mongolia as the treated area, considering that Mongolia shares a border of approximately 3,000 km with Inner Mongolia and has similar natural resources, culture, and livestock production modes (Dong et al., 2020). Most importantly, Inner Mongolia has implemented the GECP since 2011, whereas Mongolia has not been subject to similar large-scale regulations during the same period. To check the robustness of the results for Mongolia and Inner Mongolia, we extended the treated area to the whole of northern China, which includes most of the country's permanent grasslands, and used bordering areas of Russia, Mongolia, Kazakhstan, Afghanistan, Kyrgyzstan, Tajikistan, Pakistan, Bhutan, India, and Nepal, as control areas.

Although some studies have estimated the causal effects of the GECP on livestock populations and grassland conditions (e.g., Liu et al., 2019a, 2019b; Huo et al., 2021), its impacts on GHGs and air pollutants have not been studied. To estimate the causal effects of the GECP, previous studies used either a basic fixed-effects model (e.g., Liu et al., 2019a; 2019b) or a difference-in-differences (DID) model (e.g., Huo et al., 2021). Nevertheless, these methods did not consider heterogeneity in treatment effects, which may have resulted in biased estimations (de Chaisemartin and D'Haultfoeuille, 2020; Goodman-Bacon, 2021). And the parallel trend assumption was hardly satisfied in the case of the GECP. The GECP was implemented at once in the typical pastural areas of China in 2011, and Hou et al. (2021) used areas in which the GECP was not implemented during 2011–2015 (i.e., Shanxi, Hebei, Liaoning, Jilin, and Heilongjiang Provinces) as a control group. These areas are characterized by intensive livestock production and agricultural structures similar to crop areas and account for less than 6% of China's permanent grasslands (PRC, 2021). Thus, assuming common trends, such as livestock production and grassland conditions, between the treated and control areas may have led to biased results. In this study, we used the most advanced synthetic difference-in-differences (SDID) method, which does not rely on parallel trend assumptions for making causal inferences, to obtain more precise and rigorous results.

The rest of this paper is organized as follows: Section 2 introduces the study area and data sources. Section 3 presents the SDID approach. Section 4 presents the empirical results, a heterogeneity analysis, placebo tests, and falsification tests. Section 5 presents robustness checks based on different empirical methods and observations. Section 6 presents a pathway analysis. Section 7 concludes the paper. Additional details on our data and empirical results are provided in the Appendix.

2. Materials

2.1. Study area

Inner Mongolia, a province of China between 97°173′–126°066′E and 37°408′–53°334′N, covers an area of 1,183,000 km^2, accounting for 12% of China's total land area, and is home to 24 million people. More than 70% of Inner Mongolia is permanent grassland, which accounts for 27% of China's grassland area (Liu et al., 2019a). Mongolia is a country located in eastern Central Asia between 87°75′–119°924′E and 41°566′–52°155′N, covering an area of 1,564,000 km^2, mostly permanent grassland, and hosting a population of 3.3 million people. The livestock industry, dominated by natural grazing, plays a crucial role in its national economy. Fig. 1 presents geographic information on the two areas.

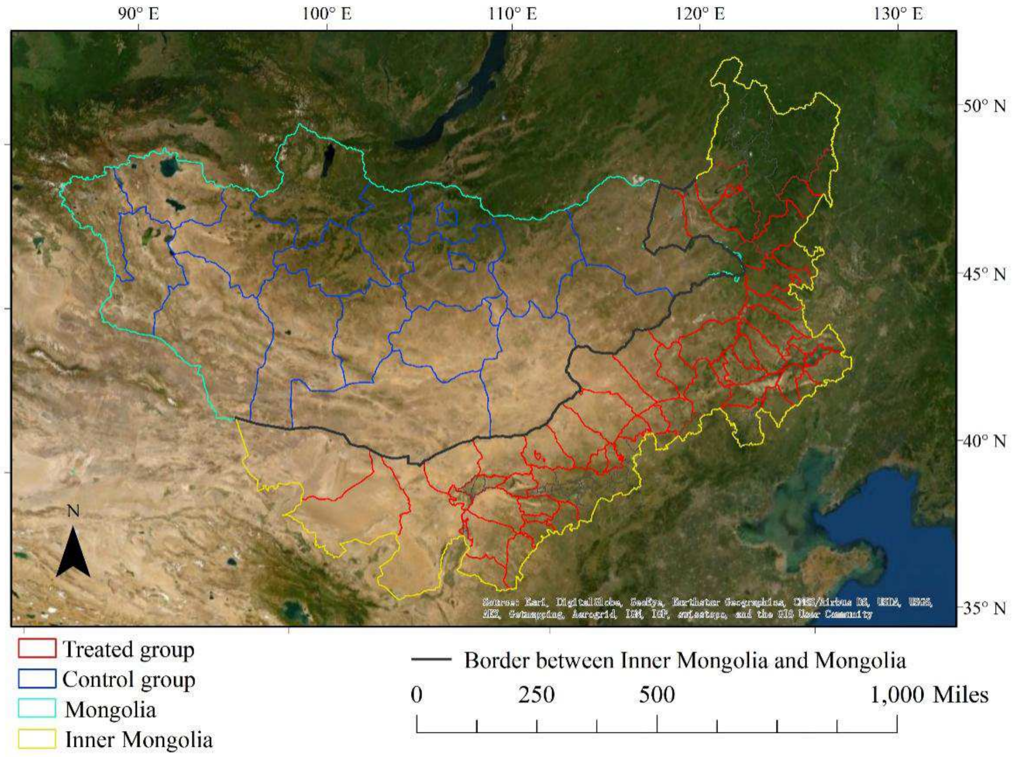
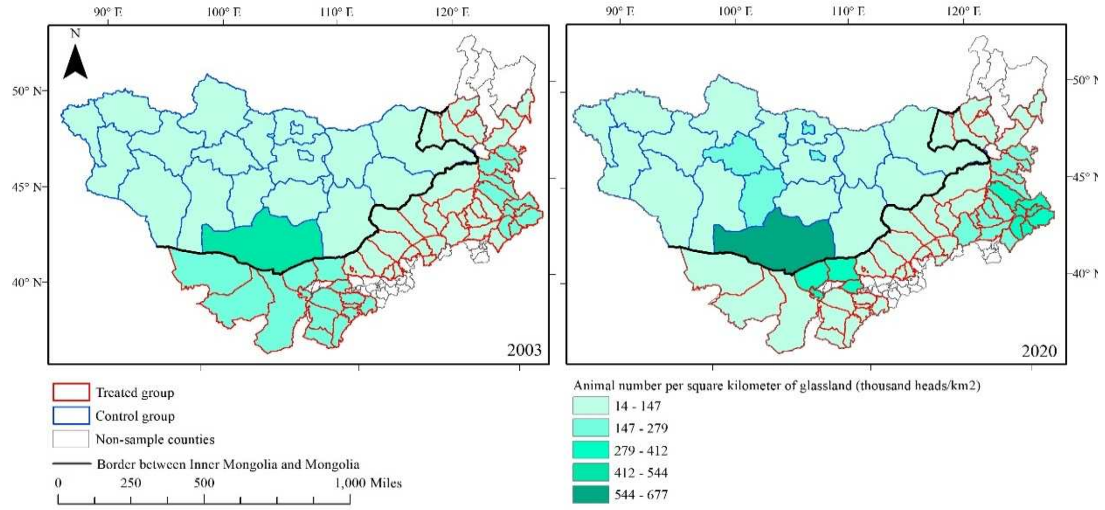


Fig. 1. Map of the research area.

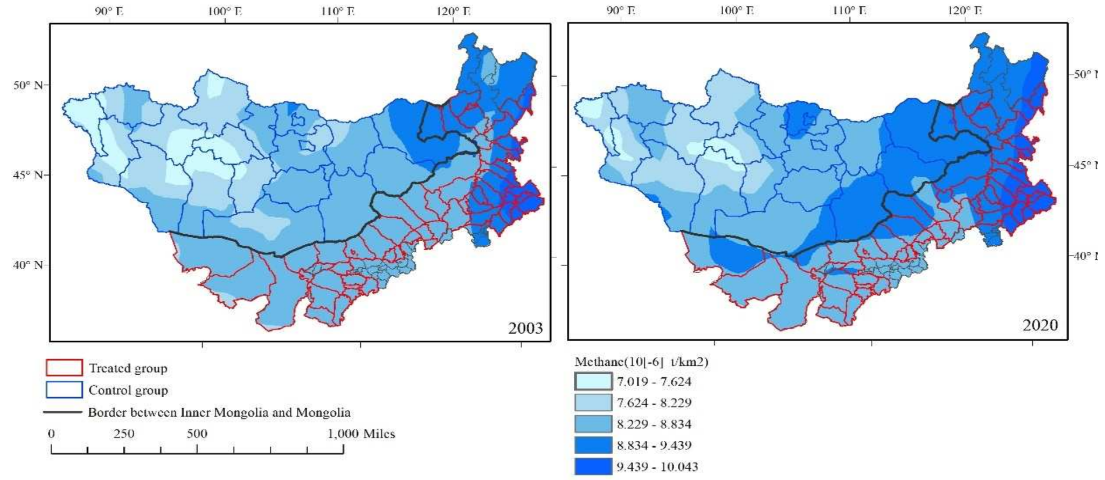
Inner Mongolia includes 103 counties. Its pastural areas are distributed in 33 pastural and 21 semi-pastural counties, which account for 81% of its total area. However, herders accounted for only 13% of its total population in 2019. The remaining 48 counties are agricultural areas with a population density considerably higher than that of pastural areas. Thus, to ensure comparability between the treated and control groups, we excluded the agricultural areas of Inner Mongolia from the analysis. The *soum* is the lowest administrative unit of Mongolia. However, the land area of a soum is considerably smaller than that of an Inner Mongolia county. Moreover, official soum-level statistical data are limited. Therefore, we focused on the *aimag* level (a level higher than the *soum*) to ensure correspondence to the county level of Inner Mongolia. Ultimately, the data set included 54 pastural and semi-pastural counties of Inner Mongolia and 22 *aimag*s (hereinafter referred to as counties) of Mongolia. Considering that the GECP has been implemented since 2011, we used the years 2003–2010 as a pretreatment period and the years 2011–2020 as the treatment period. The counties of Inner Mongolia after 2011 were the treated areas, and the rest were the control areas. An overview of the quasi-experiment is presented in Fig. A.1.

2.2. Data

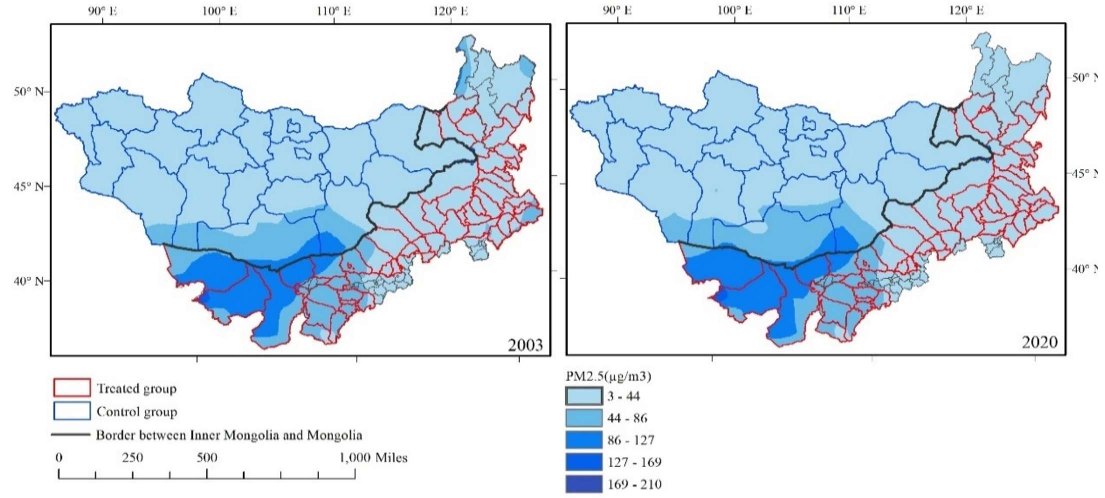
The data used in our empirical analysis included livestock populations, animal gas emissions, atmospheric GHG and air pollutant concentrations, grassland quality, carbon sequestration in grasslands, and other indicators, such as climatic conditions, land cover, and economic development.


90° E
100° E
110° E
120° E
N
50° N
45° N
40° N
2003
2020
Treated group
Control group
Non-sample counties
Border between Inner Mongolia and Mongolia
0
250
500
1,000 Miles
Animal number per square kilometer of glassland (thousand heads/km2)
14 - 147
147 - 279
279 - 412
412 - 544
544 - 677

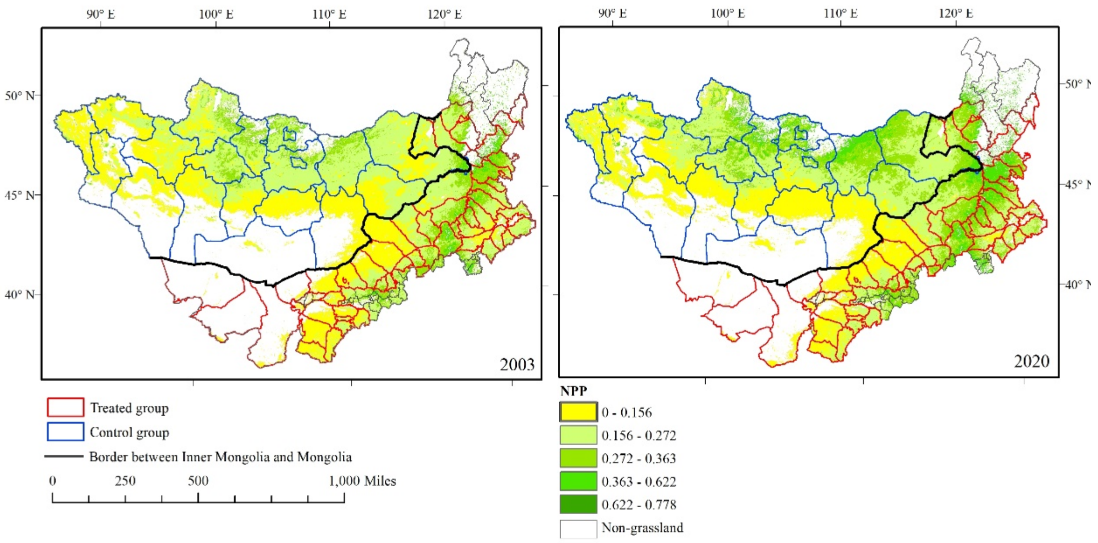
a


90° E
100° E
110° E
120° E
50° N
45° N
40° N
2003
2020
Treated group
Control group
Border between Inner Mongolia and Mongolia
0
250
500
1,000 Miles
Methane(10[-6] t/km2)
7.019 - 7.624
7.624 - 8.229
8.229 - 8.834
8.834 - 9.439
9.439 - 10.043

b


90° E
100° E
110° E
120° E
50° N
45° N
40° N
2003
2020
Treated group
Control group
Border between Inner Mongolia and Mongolia
0
250
500
1,000 Miles
PM2.5(μg/m3)
3 - 44
44 - 86
86 - 127
127 - 169
169 - 210

c



d

Fig. 2. Distributions of (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP (net primary productivity) in Mongolia and Inner Mongolia in 2003 and 2020.

2.2.1. Livestock populations

Considering that cattle and sheep are the main kinds of grazing animals in the studied pastural areas, the livestock population indicators were cattle, sheep, and total animal numbers per square kilometer of grassland. The total number of animals refers to the sum of cattle, sheep, and other animals, such as horses, donkeys, mules, and camels. We converted all animal numbers to standardized sheep units based on the feed intake of each kind of animal. For instance, one large animal (e.g., a cow or camel) was converted to 5 standard sheep units. We obtained data on the livestock populations of Inner Mongolia for the period 2003–2020 from the provincial yearbooks. Official county-level statistical data on animal numbers in Inner Mongolia are not available after 2017. Therefore, we used city-level data to calculate the livestock population of each sample county affiliated with a city. We obtained data on the county-level livestock populations of Mongolia from the census database of the country's national statistics service.

Based on official statistical data, Fig. 2(a) presents the distribution of livestock production in Inner Mongolia and Mongolia in 2003 and 2020. Fig. 3(a) shows the changes in total animal numbers in Inner Mongolia and Mongolia between 2003 and 2020, indicating that the livestock population growth rates in Inner Mongolia before the GECP were higher than those in Mongolia during the same period but became lower after the introduction of the GECP. The changes in cattle and sheep numbers in Inner Mongolia and Mongolia between 2003 and 2020 are shown in Fig. A.3.

2.2.2. Gas emissions from animals

Gas emissions from livestock production originate from four main processes: enteric fermentation, manure management, feed production, and energy consumption (FAOUN, 2010). Ruminants' enteric fermentation emits CH_4, while their manure emits CH_4, N_2O, and NH_3 (Kingston-Smith, 2010; Jin et al., 2021). CO_2 is the main gas emitted from feed production, including the production of fertilizers and the use of machinery for crop management, harvesting, processing, and transportation, which are limited in the investigated areas. Therefore, we focused on CH_4, N_2O, and NH_3 emissions from enteric fermentation and manure management, which accounted for more than 80% of the total emissions from livestock supply chains in our case. We calculated the total amounts of these gases based on the animal populations and the emission factors of each kind of animal using the emission factor method suggested by the IPCC as follows (Gavrilova et al., 2019):

$$\mathrm{CH_4}_{jit} = L_{jit} * m_i + L_{jit} * n_i, \tag{1}$$

$$\mathrm{N_2O}_{jit} = L_{jit} * p_i, \tag{2}$$

$$\mathrm{NH_3}_{jit} = L_{jit} * q_i, \tag{3}$$

where $\mathrm{CH_4}_{jit}$, $\mathrm{N_2O}_{jit}$, and $\mathrm{NH_3}_{jit}$ represent the amounts of CH_4, N_2O, and NH_3, respectively, emitted by animal kind j in county i during year t, L_{jit} is the number of animal kind j in county i in year t, and $m_i, n_i, p_i, and\ q_i$ are the different emission factors of CH_4, N_2O, and NH_3 for each kind of animal (see Table A.1). Animal CH_4 emissions include CH_4 released from enteric fermentation and manure management, whereas N_2O and NH_3 emissions involve only manure management. We converted CH_4 and N_2O to CO_2 equivalents, calculated according to the global warming potential (GWP) conversion coefficients for different GHGs provided by the IPCC (Gavrilova et al., 2019). The GWP_{100} is a measure of how much energy the emission of 1 t of CH_4 or N_2O will absorb over a 100-year time horizon relative to the emission of 1 t of CO_2 equivalent. The GWP_{100} conversion coefficients of CH_4 and N_2O are 27.9 and 273, respectively, which means that the emission of 1 t of CH_4 is equivalent to the emission of 27.9 t of CO_2, and the emission of 1 t of N_2O is equivalent to the emission of 273 t of CO_2 (IPCC, 2021).

Fig. A.3 presents the changes in CH_4, N_2O, and NH_3 emissions from animals in Inner Mongolia and Mongolia from 2003 to 2020. The growth rates of CH_4, N_2O, and NH_3 emissions from animals in Inner Mongolia before the GECP were higher than those in Mongolia during the same period, but they became lower after the GECP, which is consistent with the changes in livestock populations.

2.2.3. Atmospheric GHGs and air pollutants

We collected data on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations from the Atmosphere Data Store of the Copernicus Atmosphere Monitoring Service (CAMS), supported by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data on atmospheric N_2O and NH_3 were not available. The fourth-generation ECMWF global reanalysis of atmospheric composition (EAC4) provides data from 2003 onward at a spatial resolution of 0.75×0.75 degrees in latitude and longitude. The reanalysis combines model data with observations from around the world into a globally complete and consistent data set using an atmospheric model based on the laws of physics and chemistry (Inness et al., 2019).

Based on raw reanalysis data, Fig. 2(b) and (c) presents the distribution of atmospheric CH_4 and $PM_{2.5}$ concentrations in Inner Mongolia and Mongolia in 2003 and 2020. Fig. 3(b) and (c) shows the changes in atmospheric CH_4 and $PM_{2.5}$ concentrations in Inner Mongolia and Mongolia from 2003 to 2020. The $PM_{2.5}$ concentration growth rate in Inner Mongolia before the GECP was higher than that in Mongolia during the same period. After 2011, $PM_{2.5}$ concentrations started to decrease in both Inner Mongolia and Mongolia, but the reduction rate was faster in Inner Mongolia than in Mongolia. The distributions of and changes in PM_{10} concentrations during 2003–2020 are shown in Figs. A.2 and A.3.

2.2.4. Grassland quality

The normalized difference vegetation index (NDVI) and net primary productivity (NPP) are widely used to quantify grassland quality (e.g., Liu et al., 2018; Liu et al., 2019b). Both are commonly used as indicators of vegetation vigor (Xu et al., 2012; Liu, Liu et al., 2021). NPP refers to the total amount of new carbon fixed by a plant community through photosynthesis, thus reflecting vegetation growth status and ecosystem health (Liang et al., 2015). The NDVI is an important indicator of vegetation coverage. We acquired the MODIS product from NASA's Earth Science Data Systems Program database, which provides NPP and NDVI data at a resolution of 500 m/pixel over 16-day retrieval periods. Thus, we collected the annual NPP and maximum annual NDVI of grasslands at the county level for the period 2003–2020.

Based on the raw remote sensing data, Fig. 2(d) presents the distribution of grassland NPP in Inner Mongolia and Mongolia in 2003 and 2020. Fig. 3(d) shows the changes in grassland NPP in Inner Mongolia and Mongolia from 2003 to 2020. Before the introduction of the GECP, the NPP growth rate exhibited a decreasing trend in Inner Mongolia and an increasing trend in Mongolia. After the GECP was introduced, Inner Mongolia also showed an increasing trend, and the increase rate was faster than in Mongolia. The distributions of and changes in the NDVI are presented in Figs. A.2 and A.3.

2.2.5. Carbon sequestration of grasslands

Some studies have found that widely distributed grasslands constitute a potential carbon sink (Piao et al., 2004; Feng, 2013; Tong et al., 2018). However, the effects of the GECP on carbon sequestration in grasslands have not been empirically estimated. We calculated carbon sequestration in grasslands based on the NDVI data. Piao et al. (2004) found a significant correlation between aboveground biomass density and the maximum annual NDVI, which is expressed by Eq. (4). We converted aboveground biomass to carbon units using a conversion factor of 0.45 (Lieth and Whittaker, 2012).

$$Carbon\ storage = 197.71 * NDVI_{max}^{1.6228}. \tag{4}$$

Carbon sequestration in grasslands is, in effect, the sum of aboveground and belowground carbon. Most biomass carbon in grassland ecosystems is stored underground. Aboveground biomass carbon has been widely used to estimate belowground biomass (Feng, 2013; Liang et al., 2015). The ratios of belowground to aboveground biomass for different grassland types are presented in Table A.2.

Fig. A.3 shows the changes in carbon sequestration in grasslands in Inner Mongolia and Mongolia from 2003 to 2020. Before the GECP was introduced, the carbon sequestration growth rate in Inner Mongolia exhibited a decreasing trend, while that in Mongolia exhibited a slightly increasing trend. After the introduction of the GECP, carbon sequestration in Inner Mongolia also showed an increasing trend, and the increase rate was faster than in Mongolia.

2.2.6. Other data, including climatic conditions, land cover, and economic development

We obtained data on temperature, precipitation, wind direction, and wind speed for the period 2003–2020 (with a spatial resolution of 0.5 × 0.5 degrees in latitude and longitude) from the fifth-generation ECMWF reanalysis of the global climate and weather (ERA5) database, which was developed by the CAMS. We converted the daily temperature and precipitation data and monthly wind data to yearly data. We obtained each county's grassland, desert, and total land area data for the period 2003–2019 from MCD12Q1 version 6, developed by NASA, which provides global land cover types at a spatial resolution of 500 m at yearly intervals. We also used nighttime light data, which have been suggested to be the best available proxy measure of subnational economic growth and population density (Keola et al., 2015; Bunte et al., 2018). We obtained nighttime light intensity data at a 1 × 1 km grid cell level for the period 2001–2020 from the database of radiance measurements provided by the Visible Infrared Imaging Radiometer Suite sensor from NASA/NOAA's Suomi National Polar-orbiting Partnership satellite.

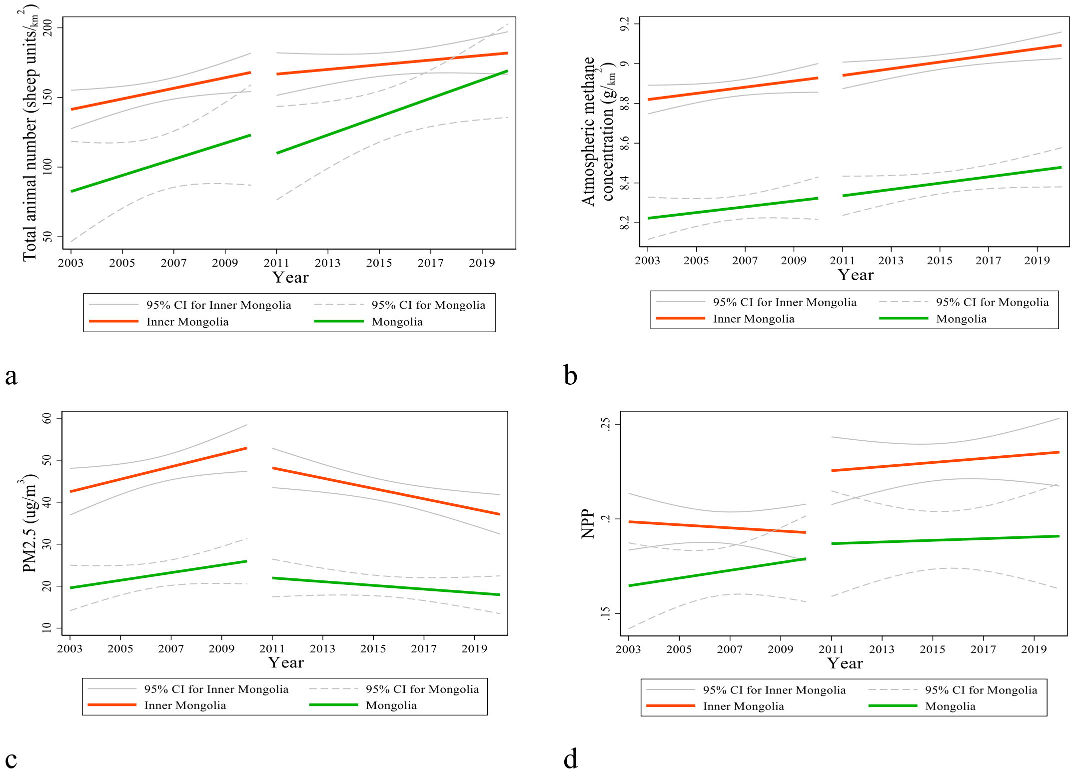


Fig. 3. Changes in (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP in Mongolia and Inner Mongolia before and after the introduction of the GECP (2001–2020).

3. Methods

We estimated the causal effects of the GECP on livestock populations, animal gas emissions, atmospheric CH_4 and air pollutant concentrations, grassland quality, and carbon sequestration in grasslands. We used SDID, a cutting-edge method for making causal inferences that combines static and dynamic SDID estimators. We then employed a fixed-effects model to investigate the relationships between livestock populations, GHGs, air pollutants, and grassland conditions. We also used the event study method as a robustness check.

3.1. Why SDID

Counterfactual analyses have been widely used to estimate policy effects. DID, event study, and synthetic control (SC) methods are the most popular. In our case, the counterfactual referred to changes in livestock production and ecosystems in the pastural areas of Inner Mongolia in the absence of the GECP and was constructed based on Mongolia, which has similar natural resources, culture, and livestock production modes, and has not implemented the GECP (Wang et al., 2013). Satisfying the parallel trend assumption is a precondition for using DID and event study methods based on two-way fixed-effects regressions. The assumption in this case was that the trends in the outcome variables did not differ between Mongolia and Inner Mongolia. However, as shown in Fig. 3, which was based on raw data, the parallel trend assumption was difficult to satisfy. Although the pretreatment trend test results for the outcome variables may be positive after control variables are included, this does not necessarily mean that there is a real parallel trend (Callaway and Sant'Anna, 2022). In this regard, a counterfactual analysis using DID and event study methods would be controversial (Kahn-Lang and Lang, 2018; Roth, 2022).

Another popular method for counterfactual analysis is SC, introduced by Abadie and Gardeazabal (2003) and Abadie et al. (2010, 2015), which has usually been used for cases with a single treated unit and no clear control group. The SC method involves identifying the optimal weighted combination of control units to match a unit of interest in the pretreatment period to a set of outcome variable predictors as closely as possible. The posttreatment change in the outcome is an estimate of the counterfactual. SC provides a better pretreatment match between a unit of interest and its counterfactual than the traditional DID method (Athey and Imbens, 2017; Campos et al., 2022). In the last few years, a growing body of econometrics research has focused on further developing the original SC method along several dimensions, including a systematic way of making inferences (Abadie, 2021). In this study, we took advantage of SDID, a recent important derivative of the SC method introduced by Arkhangelsky et al. (2021), to estimate the effects of the GECP. SDID combines features of the DID and SC methods (Arkhangelsky, 2021). Like DID, it is invariant to additive unit-level shifts and enables valid large-panel inferences. At the same time, like SC, it introduces the weightings of both pretreatment periods and cross-sectional units into the construction of a synthetic counterfactual for causal estimations. As such, unlike DID, it does not rely on parallel trend assumptions or assumptions of treatment exogeneity. Moreover, it allows for greater heterogeneity in the outcomes and has been suggested to improve the precision of the estimator (Arkhangelsky et al. 2021).

3.2. SDID method

In our case, we have a balanced panel with *N* counties and *T* years, where the outcome for county *i* in year *t* is denoted by Y_{it}, and exposure to the GECP (binary treatment) is denoted by $W_{it} \in \{0,1\}$. T_{pre} represents the years before the GECP (2001–2010), while T_{post} represents the GECP years (2011–2020). N_{co} denotes the control counties, including the counties of Mongolia and those of Inner Mongolia before T_{post}, and N_{tr} equals $N - N_{co}$, which represents the treated counties—that is, the counties of Inner Mongolia after T_{pre}. The weights of $\widehat{\omega_i^{sdid}}$ align the trends in the untreated counties with the pretreatment trends in the treated counties—for example, $\sum_{i=1}^{N_{co}} \widehat{\omega_i^{sdid}} Y_{it} \approx N_{tr}^{-1} \sum_{i=N_{co}+1}^{N} Y_{it}$ for t = 1, ..., T_{pre}. The time weights of $\widehat{\lambda_t^{sdid}}$ balance the pretreatment periods with the treatment periods—for example, $\sum_{t=1}^{T_{pre}} \widehat{\lambda_t^{sdid}} Y_{it} \approx T_{post}^{-1} \sum_{t=T_{pre}+1}^{T} Y_{it}$ for i = 1, ..., N_{co}. The weights of $\widehat{\omega_i^{sdid}}$ and $\widehat{\lambda_t^{sdid}}$ are then used in a two-way fixed-effects regression to estimate the average causal effects of the GECP, denoted by τ, as follows:

$$\left(\widehat{\tau^{sdid}}, \hat{\mu}, \hat{\alpha}, \hat{\beta}\right) = agr\ min_{\tau,\mu,\alpha,\beta} \left\{\sum_{i=1}^{N} \sum_{t=1}^{T} (Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau)^2 \widehat{\omega_i^{sdid}} \widehat{\lambda_t^{sdid}}\right\}, \tag{5}$$

where the outcome variable of Y_{it} is a vector that represents the indicators of livestock populations, animal gas emissions, atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations, and grassland conditions, W_{it} equals 1 if county i implemented the GECP in year t or 0 otherwise, α_i denotes the county fixed effects, and β_t denotes the time fixed effects.

3.3. Dynamic SDID

The results based on the basic SDID method presented in Section 3.2 represent the average causal effects during the treatment. Dynamic time-varying causal effects also have been concerned with the most recent developments in causal inferences (Goodman-Bacon, 2021; Sun and Abraham, 2021). Clarke and Tapia-Schythe (2021) estimated the causal effects of each posttreatment period. Accordingly, we first introduced dynamic SDID to estimate the causal effects in each GECP year.

In simple terms, dynamic SDID is based on estimating each policy period separately. First, an outcome matrix with two periods during the treatment period for one treated cohort is presented as

$$Y = \begin{pmatrix} Y_{co,pre} & Y_{co,post1} & Y_{co,post2} \\ Y_{tr,pre} & Y_{tr,post1} & Y_{tr,post2} \end{pmatrix},$$

where $post1$ and $post2$ are the first and second treatment periods, respectively. This matrix is further decomposed into

$$Y^1 = \begin{pmatrix} Y_{co,pre} & Y_{co,post1} \\ Y_{tr,pre} & Y_{tr,post1} \end{pmatrix},$$
$$Y^2 = \begin{pmatrix} Y_{co,pre} & Y_{co,post2} \\ Y_{tr,pre} & Y_{tr,post2} \end{pmatrix}.$$

The above submatrices can be estimated using SDID to obtain the causal effects in the first and second treatment periods. Therefore, in the simplest two-period case, the causal effects of the GECP in each policy year are calculated as

$$\hat{\tau}_{t'} = \left[\left(Y_{it} - \sum_1^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it}\right)\right] - \left[\sum_{i=1}^{N_{co}} \widehat{\omega}_i^{\ sdid} \left(Y_{it} - \sum_1^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it}\right)\right], \tag{6}$$

where t' is the treatment period. Compared with Eq. (5), in Eq. (6), there is only one treated unit, in which N_{tr} equals 1, and the sum of all treated units ($\sum_{i=N_{co}+1}^{N}$) also equals 1. Thus, the effects of the treatment that equals the outcome of each treated unit minus the synthetic outcome are calculated as $(Y_{it} - \sum_{1}^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it})$. Similarly, if there is only one treatment period, we have $T_{post} = 1$, and the sum of all treatment periods ($\sum_{t=T_{pre}+1}^{T}$) also equals 1.

This is now generalized to a situation with multiple cohorts and treatment periods. If there are more than one treated unit and more than one treatment period—that is, $N_{tr} > 1$ and $T_{post} > 1$—that have the same treatment starting time, the outcome matrix is presented as

$$\boldsymbol{Y} = \begin{pmatrix} \boldsymbol{Y}_{co,pre} & \boldsymbol{Y}_{co,post1} & \boldsymbol{Y}_{co,post2} \cdots & \boldsymbol{Y}_{co,postT} \\ \boldsymbol{Y}_{tr,pre} & \boldsymbol{Y}_{tr,post1} & \boldsymbol{Y}_{tr,post2} \cdots & \boldsymbol{Y}_{tr,postT} \end{pmatrix},$$

where the outcome matrix of the treatment group is $\boldsymbol{Y}_{tr:} = \begin{pmatrix} \boldsymbol{Y}_{tr1:} \\ \vdots \\ \boldsymbol{Y}_{trN:} \end{pmatrix}$. Because we do not consider variations in the treatment effects between the treated units, we combine the outcome matrices of different treatment groups into one. Nevertheless, we decompose the treatment effects in multiple treatment periods into a submatrix for each period:

$$\boldsymbol{Y^1} = \begin{pmatrix} \boldsymbol{Y}_{co,pre} & \boldsymbol{Y}_{co,post1} \\ \boldsymbol{Y}_{tr,pre} & \boldsymbol{Y}_{tr,post1} \end{pmatrix},$$

$$\boldsymbol{Y^2} = \begin{pmatrix} \boldsymbol{Y}_{co,pre} & \boldsymbol{Y}_{co,post2} \\ \boldsymbol{Y}_{tr,pre} & \boldsymbol{Y}_{tr,post2} \end{pmatrix},$$

$$\vdots$$

$$\boldsymbol{Y^T} = \begin{pmatrix} \boldsymbol{Y}_{co,pre} & \boldsymbol{Y}_{co,postT} \\ \boldsymbol{Y}_{tr,pre} & \boldsymbol{Y}_{tr,postT} \end{pmatrix}.$$

The estimator of each treatment period is

$$\hat{\tau}_{t'} = \left[\frac{1}{N_{tr}} \sum_{i=N_{co}+1}^{N} \left(Y_{it} - \sum_{1}^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it}\right)\right] - \left[\sum_{i=1}^{N_{co}} \widehat{\omega}_i^{\ sdid} \left(Y_{it} - \sum_{1}^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it}\right)\right], \quad (7)$$

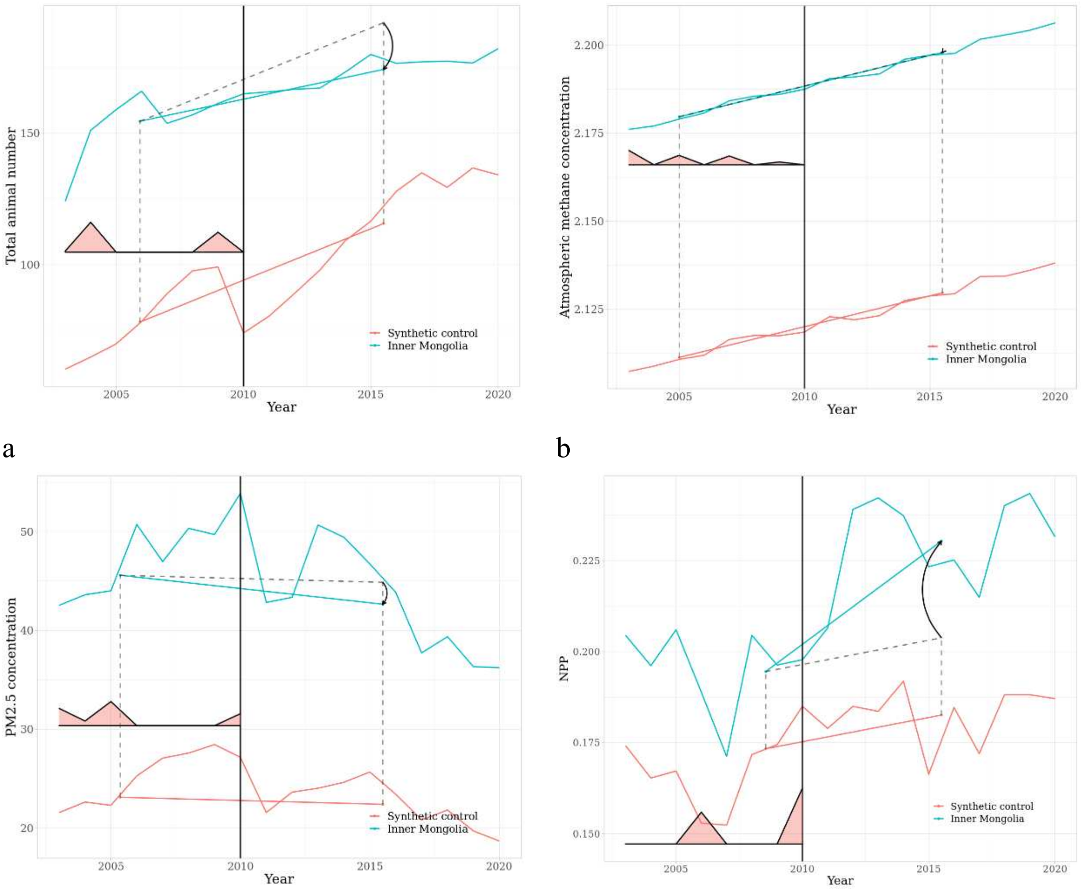
where $t^{'} \in \{post1, post2, \cdots, postT\}$ represents each GECP year. Compared with Eq. (6), Eq. (7) has an additional weighted average term for the treated units—that is $\frac{1}{N_{tr}} \sum_{i=N_{co}+1}^{N} \left(Y_{it} - \sum_{1}^{T_{pre}} \hat{\lambda}_t^{\ sdid} Y_{it}\right)$, where $\frac{1}{N_{tr}}$ is the weight for the causal effects on each treated unit.

4. Results

4.1. Empirical results

4.1.1. Average causal effects

Based on the SDID method, Fig. 4 presents the average trends in the causal effects of the GECP on the number of animals, atmospheric CH_4 and $PM_{2.5}$ concentrations, and grassland quality (NPP) during 2003–2020 in the treated counties of Inner Mongolia and the relevant weighted averages of the control counties of Mongolia (synthetic control). Table 1 displays the corresponding causal effects of the GECP on all outcome variables.



a b

c d

Fig. 4. Estimated causal effects of the GECP on (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP based on the SDID method**.**

Note: The weights shown by red humps at the bottom of each graph to average the pretreatment periods (Arkhangelsky et al., 2021). The solid straight blue lines represent the observed data for the treated counties of Inner Mongolia. The dashed diagonal black lines present the unobserved counterfactuals if the GECP had not been implemented in Inner Mongolia, which were simulated based on the changes in the synthetic control group over time. The estimated decreases/increases are indicated by the gaps between the solid straight blue lines and the dashed diagonal black lines, marked by downward or upward arrows.

4.1.1.1. Impact on livestock populations

As shown in Fig. 4(a), the GECP led to a significant reduction in livestock populations. As shown in Table 1, the cattle number decreased by 4 sheep units/km^2/year, the sheep number decreased by 15 sheep units/km^2/year, and the total animal number decreased by 18 sheep units/km^2/year, on average, ceteris paribus, across the pastural areas of Inner Mongolia due to the implementation of the GECP during 2011–2020. Based on these results, we estimated that the annual cattle population would have been 32 million sheep units if the GECP had not been implemented in the pastural areas of Inner Mongolia, whereas the real cattle population was 30 million per year, on average, after 2011 (NBSC, 2021). Similarly, the annual sheep population would have been 57 million sheep units, while the real sheep population was 49 million. The total animal population would have been 98 million sheep units, compared to the actual 89 million. That is, the animal population was reduced by 10 million sheep units every year due to

GECP during 2011–2020, while other factors that can increase livestock populations, such as the producer prices of animals, remained constant.

4.1.1.2. Impact on GHGs and air pollutants

The GECP resulted in obvious decreases in CH_4, N_2O, and NH_3 emissions from animals as a direct consequence of livestock reduction, as shown in Fig. A.4, which is consistent with the results reported in Table 1. Most importantly, atmospheric CH_4 and $PM_{2.5}$ concentrations showed decreasing trends after the introduction of the GECP, as indicated by the downward arrows in Fig. 4(b) and (c). As shown in Table 1, $PM_{2.5}$ and PM_{10} concentrations decreased by 2 and 3 μg/m^3/year, respectively, due to the GECP.

4.1.1.3. Impact on grassland quality and carbon sequestration

The implementation of the GECP increased grassland quality, as shown in Fig. 4(d) on NPP and Fig. A.4 on NDVI. As shown in Table 1, the GECP led to average NPP and NDVI increases of 0.027 and 0.023, respectively, each year during 2011–2020. Carbon sequestration also increased, as indicated by the upward arrow in Fig. A.4, which is in line with previous studies suggesting that large-scale ecological restoration improves carbon sequestration (Piao et al., 2004; Feng, 2013; Tong et al., 2018).

Table 1

Estimated effects of the GECP on livestock production, greenhouse gases, air pollution, and grassland conservation during 2011–2020 based on the SDID method.

Variable	ATT	SE
Cattle number	−4.107**	1.991
Sheep number	−15.331**	8.282
otal animal number	−17.740***	7.292
Animal–CH_4	−0.461***	0.045
Animal–N_2O	−0.457***	0.069
Animal–NH_3	−0.497***	0.060
Air–CH_4	−0.0001**	0.00004
$PM_{2.5}$	−2.212**	0.939
PM_{10}	−2.767*	1.487
NPP	0.027***	0.004
NDVI	0.023**	0.011
arbon sequestration	0.042*	0.025

Notes: Due to the data characteristics (high dispersion), the animal–CH_4, animal–N_2O, animal–NH_3, air–CH_4, and carbon variables sequestration are in log form. This also applies to the rest of the analysis based on SDID. ATT is the Average effect of the Treatment on the Treated. SE is the standard error. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.1.2. Dynamic causal effects

Fig. 5 presents the causal effects of the GECP in each policy year based on the dynamic SDID method. Fig. 5(a)–(c) shows the dynamic effects of the GECP on the cattle number, sheep number, and total animal number each year due to the GECP. The total animal number reduction rate increased each year during the first round of the GECP (2011–2015), began to plateau during 2016–2019, and decreased in 2020. Nevertheless, the reduction was obviously greater during the second round (2016–2020) than during the first round.

Fig. 5(d) and (e) presents the causal effects of the GECP on atmospheric CH_4 and $PM_{2.5}$ concentrations in each policy year. The effects were unstable and nonsignificant during 2011–2015, but those during 2016–2020 were significant and negative, especially on $PM_{2.5}$. This suggests that the impacts of the GECP on mitigating GHGs and air pollutants were stronger during the second round. As shown in Fig. 5(f), NPP increased significantly each year during 2011–2020.

The dynamic effects of the GECP on animal gas emissions, PM_{10} concentrations, NDVI, and carbon sequestration each year during 2011–2020 are presented in Fig. A.5. The increase in carbon sequestration was statistically significant only during the second round of the GECP (2016–2020), suggesting that grassland restoration due to the GECP had a lag effect on carbon sequestration.

A comparison between the two rounds of the GECP indicated that the second round had stronger effects than the first round, although the main GECP elements did not differ between the two rounds. This suggests that persistence in pursuing eco-environmental policies is important because the effects on ecosystem become significant after several years of continuous implementation.

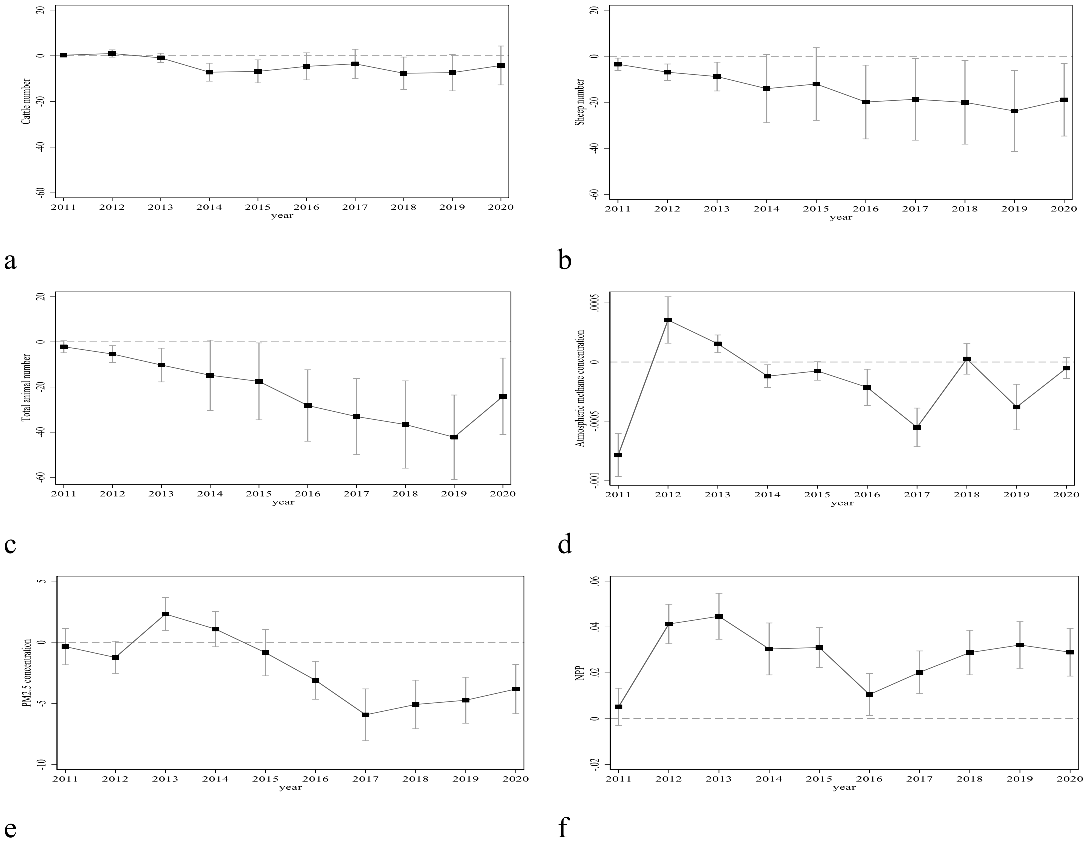


Fig. 5. Estimated dynamic effects of the GECP on (a) cattle number, (b) sheep number, (c) livestock populations, atmospheric (d) CH_4 and (e) $PM_{2.5}$ concentrations, and (f) grassland NPP during 2011–2020 based on the dynamic SDID method.

4.2. Heterogeneity analysis

We performed a heterogeneity analysis to reveal the effects of the GECP in different areas. We divided the counties into lower and higher grassland quality groups according to the NPP of each county's grassland. To divide the counties into equal groups, we calculated the average NPP of each county during 2003–2020 and ranked all the counties according to the average NPP. We then assigned the counties with NPP below the median to the lower quality group and those with NPP above the median to the higher quality group. Similarly, we divided all counties into smaller and larger grassland area groups according to each county's grassland area.

As shown in Table 2, in the lower grassland quality group, the cattle number decreased by 4 sheep units/km^2/year due to the GECP, the sheep number decreased by 16 sheep units/km^2/year, and the total animal number decreased by 27 sheep units/km^2/year. Animal CH_4, N_2O, and CH_4 emissions decreased significantly. $PM_{2.5}$ and PM_{10} concentrations decreased by 3 and 5 μg/m^3/year, respectively. NPP increased by 0.015. In the higher grassland quality group, although the reduction in livestock was statistically nonsignificant, animal CH_4, N_2O, and CH_4 emissions decreased significantly. $PM_{2.5}$ and PM_{10} concentrations decreased by 2 and 3 μg/m^3/year, respectively. NPP increased by 0.028. A comparison between the two groups indicates that the policy effects on livestock reduction were more pronounced in the lower grassland quality group. The effects on reducing animal gas emissions and $PM_{2.5}$ and PM_{10} concentrations were more evident in the lower quality group than in the higher quality group. Nevertheless, NPP increased more in the higher quality group. This is because grassland restoration progresses faster in areas with better natural endowment.

A comparison between counties with smaller grassland areas and those with larger grassland areas showed that livestock populations, especially sheep, decreased more drastically in the smaller grassland area group. Correspondingly, the reduction in animal gas emissions was greater in this group. Moreover, in the smaller grassland area group, atmospheric CH_4 concentrations decreased significantly, whereas $PM_{2.5}$ and PM_{10} concentrations did not. Conversely, in the larger grassland area group, the reduction in atmospheric CH_4 concentrations was not significant, whereas $PM_{2.5}$ and PM_{10} concentrations decreased significantly—by 3 and 5 μg/m^3/year, respectively. NPP increased significantly in both groups, but the increase was larger in the smaller grassland area group. In sum, in counties with smaller grassland areas, the reduction in livestock was greater, and the effects on reducing GHGs and promoting grassland conservation were stronger, but the effects on mitigating air pollution were not significant.

Table 2

Heterogeneity analysis based on the SDID method.

Variable	Grassland quality				Grassland area			
	Lower		Higher		Smaller		Larger	
	ATT	SE	ATT	SE	ATT	SE	ATT	SE
Cattle number	−3.822*	2.031	−3.301	3.388	−9.736	7.021	−6.842***	1.622
Sheep number	−16.420***	5.361	12.903	10.237	−25.310**	12.705	−0.844	3.237
Total animal number	−26.984***	6.833	−3.269	11.948	−46.475**	19.675	−11.312**	5.028
Animal−CH_4	−0.514***	0.095	−0.277***	0.073	−0.448***	0.141	−0.401***	0.058
Animal−N_2O	−0.518***	0.075	−0.279***	0.077	−0.454***	0.129	−0.404***	0.059
Animal−NH_3	−0.533***	0.065	−0.256**	0.112	−0.495***	0.133	−0.435***	0.060
Air−CH_4	−0.00008	0.00006	−0.00009	0.00008	−0.00014**	0.00006	−0.00008	0.00007
$PM_{2.5}$	−3.081*	1.759	−1.894***	0.732	0.706	0.746	−3.452***	1.202
PM_{10}	−4.753**	1.941	−2.801**	1.402	1.048	1.445	−5.199***	1.667
NPP	0.015***	0.005	0.028**	0.011	0.034**	0.015	0.022***	0.004
NDVI	0.008	0.012	−0.006	0.020	−0.011	0.025	0.010	0.012
Carbon sequestration	0.043	0.091	−0.049	0.072	0.040	0.074	−0.036	0.046

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.3. Placebo test

We used Mongolia and pretreatment (2001–2010) Inner Mongolia in placebo tests. First, we randomly selected some counties in Mongolia and assigned them to a hypothetical group that implemented the GECP starting in 2011. We used the remaining counties of Mongolia as a control group. As shown in Table 3, the hypothetical implementation of the GECP in Mongolia did not cause significant changes in livestock populations, animal gas emissions, atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations, or grassland conditions.

Moreover, we used 2008, 2009, and 2010 as hypothetical GECP introduction years. As shown in Table 3, the hypothetical GECP did not cause the same changes as the actual GECP, which was introduced in 2011 (see Table 1). For instance, the cattle, sheep, and total animal numbers increased with the hypothetical GECP instead of decreasing. Similarly, animal gas emissions increased, while atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations did not show significant reductions, and grassland quality and carbon sequestration did not increase. These results, which ran counter to those reported in Table 1, confirmed that livestock populations, animal gas emissions, CH_4, $PM_{2.5}$, and PM_{10} concentrations, and grassland conditions changed due to the introduction of the GECP in 2011, verifying the validity of the causal effects presented in Table 1.

Table 3

Placebo test based on the SDID method.

Variable	Mongolia		2008		2009		2010	
	ATT	SE	ATT	SE	ATT	SE	ATT	SE
Cattle number	3.722	2.580	2.711*	1.441	3.260***	1.117	9.804***	1.757
Sheep number	12.436	10.109	2.371	2.171	12.428***	4.206	20.625***	6.418
Total animal number	23.376	14.237	7.157	4.625	17.081***	4.249	31.257***	10.426
Animal–CH_4	0.071	0.072	0.116**	0.051	0.147***	0.036	0.256***	0.057
Animal–N_2O	0.073	0.068	0.120***	0.044	0.145***	0.031	0.256***	0.056
Animal–NH_3	0.078	0.083	0.090	0.060	0.149***	0.033	0.261***	0.066
Air–CH_4	0.00000	0.00006	−0.00007	0.00012	0.00003	0.00007	0.0004***	0.0001
$PM_{2.5}$	−0.779	1.128	0.178	0.976	1.638	1.457	5.115***	1.474
PM_{10}	−1.385	1.828	−0.313	1.645	1.475	2.849	7.669***	1.807
NPP	−0.0005	0.004	−0.012**	0.005	−0.020***	0.006	−0.023***	0.007
NDVI	0.017	0.011	−0.014**	0.007	−0.038***	0.010	−0.031***	0.008
Carbon sequestration	0.080	0.066	−0.007	0.038	−0.138***	0.030	−0.108***	0.040

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.4. Falsification test

We aimed to exclude the possibility that the decreases in atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations were caused by changes in industry or other considerable factors. In 2014, 40.2% of the total anthropogenic CH_4 emissions in China were attributed to the agricultural industry, mainly livestock production and rice farming, and 44.8% were from the energy sector, such as coal mining and oil and gas exploitation (PRC, 2018). In 2020, 65.6% of PM emissions were from industrial sources, and 33% were from mobile sources, such as cars and trucks (MEEPRC, 2022). Therefore, biases in the estimation of the causal effects of livestock reduction due to the GECP are possible.

In Inner Mongolia, industry development is restricted because of its adverse effects on eco-system protection—especially its pastural areas. In 2020, gross agricultural production accounted for 18.33% of the region's gross domestic product, which was considerably higher than the national average (7.65%) (NBSC, 2021). Moreover, cropland accounted for only 9.16% of the region's total area, while grassland accounted for 77.78%. This shows that its agricultural sector is dominated by the livestock industry. Therefore, it is conceivable that the livestock industry has a significant effect on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations.

More importantly, as shown in Table 4, the causal effects of the GECP on secondary industry and local economic growth, estimated on the basis of nighttime light intensity, were not significant. This suggests that the decreases in atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations with the GECP were not related to changes in local secondary industry or economic development. Furthermore, the GECP resulted in a significant increase in cropland area. GHG and air pollutant emissions should increase with the development of crop farming. However, the decreases in atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations due to the GECP suggest that crop farming did not have a significant effect. Thus, the falsification tests performed to exclude possible biases (Cunningham, 2021) showed that the decreases in atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations were caused by livestock reduction with the implementation of the GECP since 2011 and were not related to changes in the local economy, industry, or crop farming.

Table 4

Estimated effects of the GECP on economic development and crop farming during 2011–2020 based on the SDID method.

Variable	ATT	SE
Secondary industry	−0.028	0.030
Nighttime light intensity	−0.011	0.023
Cropland area	0.316**	0.130

Notes: Due to the data characteristics (high dispersion), the nighttime light intensity and cropland area variables are in log form. $^{**}p < 0.05$.

5. Robustness check

We conducted an SDID analysis considering covariates and used the event study method to check the robustness of the main empirical results. Moreover, we extended the study area, adding the whole of northern China, which includes most of China's permanent grasslands, to the treated group, and the corresponding bordering areas of Russia, Mongolia, Kazakhstan, Afghanistan, Kyrgyzstan, Tajikistan, Pakistan, Bhutan, India, and Nepal, to the control group.

5.1. SDID with covariates

Table 5 presents the causal effects of the GECP on the outcome variables of interest considering covariates (Kranz, 2022) that potentially impact livestock populations, including local economic development, grassland quality, and grassland area. To estimate the effects of the GECP on animal gas emissions, atmospheric GHGs, and air pollutant concentrations, we controlled the variables of wind direction, wind speed, grassland area, and local economic development. For grassland quality, the covariates included livestock populations and climate factors such as temperature, precipitation, drought, and freezing weather. The results reported in Table 5 are consistent with the results obtained without considering covariates (Table 1), demonstrating their robustness.

Table 5

Estimated effects of the GECP with covariates based on the SDID method.

Variable	ATT	SE
Cattle number	−5.202**	2.155
Sheep number	−12.970*	7.348
Total animal number	−20.807***	7.650
Animal–CH_4	−0.444***	0.064
Animal–N_2O	−0.438***	0.062
Animal–NH_3	−0.478***	0.078
Air–CH_4	−0.0001**	0.00006
$PM_{2.5}$	−2.153**	1.083
PM_{10}	−2.686*	1.575
NPP	0.025***	0.004
NDVI	0.017**	0.008
Carbon sequestration	−0.003	0.028

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

5.2. Event study method

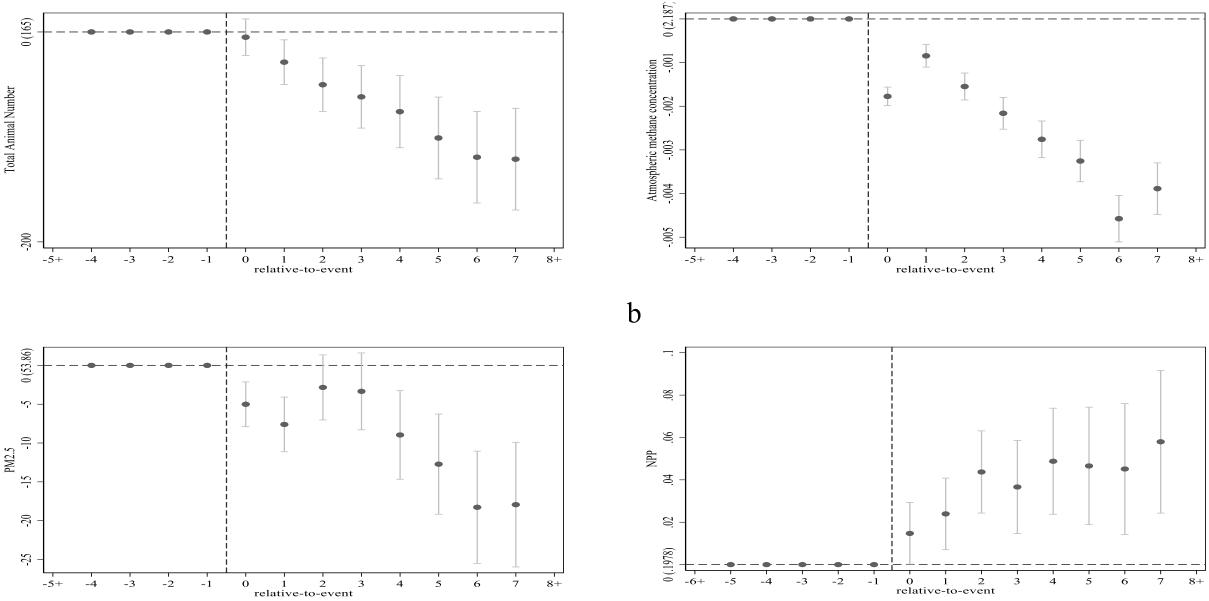
For a robustness check, we used the event study method to estimate the causal effects of the GECP. Following the relevant literature (Beck et al., 2010), we developed the following event study model:

$$Y_{it} = g_i + \sum_{\substack{t=2003 \\ t\neq 2010}}^{2020} d_{1t}\,(Treat_i * Period_t) + d_2 X_{it} + year_t + \gamma_{it}, \quad (8)$$

where Y_{it} is a vector that includes the variables of total animal number, atmospheric CH_4 and $PM_{2.5}$ concentrations, and grassland NPP, $Treat_i$ is a dummy variable indicating whether the GECP was implemented in county i, and $Period_t$ is a dummy variable indicating whether the GECP was implemented in year *t*. The year 2010, the year before the GECP started, is used as the base year. X_{it} is a set of control variables, which were the same as those used in the SDID method presented in Section 5.1. The coefficient d_{1t} represents the effects of the GECP in each year, while γ_{it} is an error term. We performed a two-way fixed-effects regression analysis that controlled for time-invariant factors at the county level (g_i) and the time variable ($year_t$). The definitions and statistics of all related variables are presented in Table A.3.

Fig. 6 shows the estimated causal effects of the GECP as deviations of the event–time coefficients of the dependent variables from the extrapolated linear trends (Freyaldenhoven et al., 2019, 2021). Fig. A.6 shows the estimated results based on the basic event study method. The assumption of parallel trends before the GECP was not satisfied. For instance, atmospheric CH_4 concentrations exhibited a continuously increasing trend during the last four years before the GECP. Therefore, we extrapolated confounders from the pretreatment periods to remove trends that might have been caused by unobserved confounders before the implementation of the GECP, such as unknown economic or environmental policies (Freyaldenhoven et al., 2019, 2021), as presented in Fig. 6.

As shown in Fig. 6, the implementation of the GECP caused significant reductions in the total animal number and atmospheric CH_4 and $PM_{2.5}$ concentrations and increases in NPP. Furthermore, the policy impacts were stronger in the later GECP years. These findings are consistent with the results obtained by the SDID and dynamic SDID methods, demonstrating the robustness of our empirical results. Moreover, the nonparallel trends before the GECP (Figs. A.6 and A.7) suggest that the changes in the outcome variables differed between Inner Mongolia and Mongolia before the GECP, confirming that Hou et al.'s (2021) estimations of the causal effects of the GECP based on DID method are biased.



a

b

c

c

Fig. 6. Estimated impacts of the GECP on (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP based on extrapolating confounders from the pretreatment periods.

5.3. *Evidence from extended sample areas*

According to the third national land survey of China in 2021 (PRC, 2021), 94% of China's permanent grasslands are concentrated in Tibet, Inner Mongolia, Xinjiang, Qinghai, Gansu, and Sichuan. In 2020, these six provinces produced 40% of China's cattle and 53% of its sheep and goats (NBSC, 2021; PRC, 2021). To further assess the robustness of our empirical results, we added all these typical grasslands to the treated group.

Fig. 7 presents the extended sample areas. These areas are close to national border lines and cross those provinces that include most of China's permanent grasslands. Moreover, most adjacent areas across China's borders are also permanent grasslands, distributed in different countries, such as Russia, Mongolia, Kazakhstan, Afghanistan, Kyrgyzstan, Tajikistan, Pakistan, Bhutan, India, and Nepal. We assigned the extended sample areas in China after 2011, when the GECP was introduced, to the treated group and the sample areas across the borders to the control group.

We obtained remote sensing data on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations, NPP, and NDVI. However, subnational-level data on livestock populations in some countries of interest were not available. Thus, we estimated the causal effects of the GECP only on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations and grassland quality at the grid level (one grid = 30 × 30 km). To estimate the effects on grassland quality, we excluded grids that did not contain grasslands. Considering natural endowment heterogeneity, we divided the extended sample areas into four buffers according to their distances from China's borders: 0–100, 100–200, 200–300, and 300–400 km.

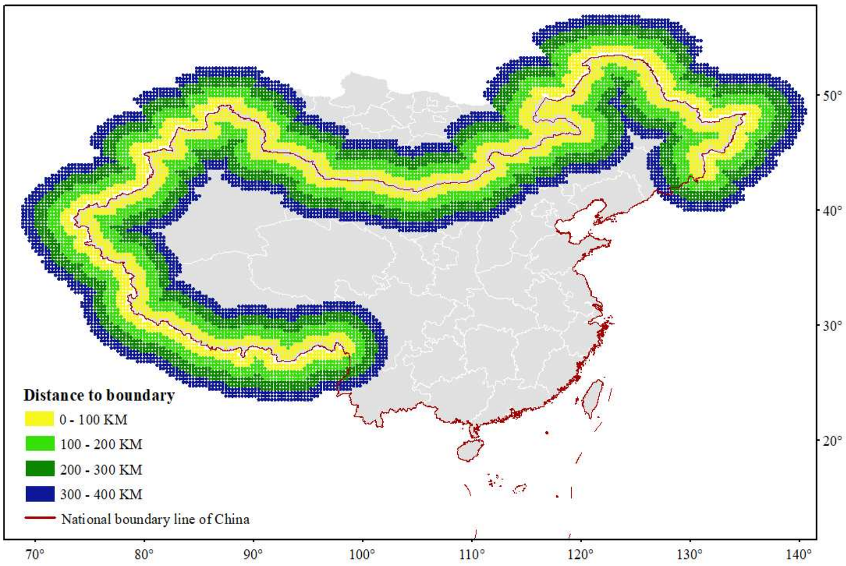


Fig. 7. Sample areas across China's borders.

Table 6 presents the effects of the GECP on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations, NPP, and NDVI in the extended sample areas. Generally, atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations decreased, while the NDVI and NPP increased due to the GECP, although some areas showed opposite trends. The main results are consistent with the results obtained from the sample areas of Inner Mongolia and Mongolia (Table 1), further confirming their robustness. The opposite effects in some buffer areas might be because the implementation of the GECP in some areas of China was weak or because some areas in the control countries were subject to unobserved large-scale environmental protection regulations during 2011–2020.

Table 6

Estimated causal effects of the GECP based on the extended sample areas.

Variable	Buffer: 0–100 km		Buffer: 100–200 km		Buffer: 200–300 km		Buffer: 300–400 km	
	ATT	SE	ATT	SE	ATT	SE	ATT	SE
Air–CH_4	0.0002***	0.00003	0.00009*	0.00005	−0.0004***	0.00007	−0.0007***	0.0001
$PM_{2.5}$	−0.139	0.146	0.229	0.179	−1.582***	0.400	−4.672***	0.484
PM_{10}	−0.482**	0.197	0.325	0.250	−1.824***	0.544	−6.183***	0.724
NPP	0.0003	0.001	−0.006***	0.001	−0.003**	0.001	0.005***	0.002
NDVI	0.009***	0.003	−0.003	0.002	0.011***	0.003	0.020***	0.002

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

6. Pathway analysis

6.1. Relationships between livestock, GHGs, air pollutants, and grasslands

We used the two-way fixed-effects model to assess the relationships between livestock, GHGs, air pollutants, and grasslands. We derived the following model specification from the general fixed-effects model:

$$Y_{it} = f_i + a_1 T_{it} + a_2 W_{it} + year_t + \zeta_{it}, \tag{9}$$

$$Z_{it} = h_i + b_1 Y_{it} + b_2 V_{it} + year_t + \delta_{it}, \tag{10}$$

where *i* and *t* denote county *i* and year *t*, respectively. Eq. (9) estimates the direct impacts of livestock reduction, given that livestock populations are considered to directly affect animal gas emissions and grassland quality (Steinfeld et al., 2006; Houzer and Scoones, 2021; Liu, Liu, et al., 2021). The dependent variable Y_{it} is a vector that represents animal CH_4, N_2O, and NH_3 emissions and NPP. The direct impacts of livestock reduction are represented by the coefficients of T_{it} in Eq. (9).

Eq. (10) estimates the indirect impacts of livestock reduction. The dependent variable Z_{it} is a vector that denotes atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations. Although atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations are not directly impacted by livestock populations, they might be influenced by animal gas emissions and grassland quality, which are directly affected by livestock populations. Theoretically, CH_4 emissions from animals may impact local atmospheric CH_4 concentrations. $PM_{2.5}$ and PM_{10} concentrations are also possibly affected by animal gas emissions and grassland conditions, given that N_2O and NH_3 are the main precursors of $PM_{2.5}$ (Gu et al., 2021; Liu et al., 2022) and that vegetation can reduce PM through sedimentation (Chen et al., 2016; Krasnov, 2016). The coefficients of Y_{it} in Eq. (10) should verify the relationship between animal CH_4 emissions and atmospheric CH_4 concentrations and identify the factors that indirectly impact $PM_{2.5}$ and PM_{10} concentrations.

W_{it} and V_{it} are vectors of control variables. For instance, climate indicators are controlled in Eqs. (10) and (11) because studies have shown that temperature and precipitation significantly affect grassland quality and the formation of GHGs and air pollutants (Fu et al., 2020). Local economic growth, represented by nighttime light intensity, is controlled in Eq. (10) because it is considered a major source of GHGs and air pollutants (Yan and Wu, 2016; Luo et al., 2017). Wind direction and wind speed are also controlled in Eq. (10) (Deryugina et al., 2019). Moreover, $year_t$ controls for time variance, f_i and h_i represent the county fixed effects that control for time-invariant county-level factors, and ζ_{it} and δ_{it} are error terms.

Table 7
Relationships between livestock, GHGs, air pollutants, and grasslands based on the two-way fixed-effects model.

	Direct impacts				Indirect impacts						
Variable	(1) Animal–CH_{4it}	(2) Animal–N_2O_{it}	(3) Animal–NH_{3it}	(4) NPP	(5) Air–CH_4	(6) $PM_{2.5}$	(7) $PM_{2.5}$	(8) $PM_{2.5}$	(9) PM_{10}	(10) PM_{10}	(11) PM_{10}
Cattle number	0.507***	0.502***	0.369***								
	(0.048)	(0.051)	(0.049)								
Sheep number	0.238***	0.232***	0.347***								
	(0.033)	(0.034)	(0.037)								
Total animal number				−0.034***							
				(0.010)							
Animal–CH_{4it}					0.0002***	−0.025			−0.017		
					(0.000)	(0.035)			(0.034)		
Animal–N_2O_{it}							−0.027			−0.019	
							(0.034)			(0.034)	
Animal–NH_{3it}								−0.055			−0.050
								(0.039)			(0.039)
NPP					0.0034***	−0.744***	−0.744***	−0.722***	−0.710***	−0.710***	−0.690***
					(0.001)	(0.243)	(0.243)	(0.243)	(0.240)	(0.240)	(0.240)
Control variables				YES	YES	YES	YES	YES	YES	YES	YES
County FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Adjusted R^2	0.889	0.878	0.863	0.385	0.998	0.421	0.421	0.423	0.413	0.413	0.415
Observations	1,368	1,368	1,368	1,216	1,292	1,292	1,292	1,292	1,292	1,292	1,292

Notes: The definitions and statistical descriptions of all variables are provided in Table A.3. The weighted producer price was deflated by the CPI, and data were not available for 2019 and 2020. The cattle number, sheep number, and total animal number variables are in log form. The control variables for NPP include temperature, precipitation, drought, and freezing weather. The control variables for atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations include grassland area, local economic development, temperature, precipitation, wind direction, and wind speed. The values in parentheses are robust standard errors. ***$p < 0.01$.

The results presented in columns (1)–(4) of Table 7 based on Eq. (9) show that livestock reduction significantly reduced animal gas emissions and improved grassland quality. Because livestock populations and grassland quality have opposite causalities, we used the variable of weighted producer price in county i in year t as an instrumental variable to solve the endogeneity problem. The weighted producer price is equal to the weighted local procurement prices of sheep and cattle, and the weight is the ratio of the sheep number to the total animal number. The weighted producer price is a valid instrumental variable because fluctuations in the local procurement price caused by national market trends are exogenous and impact livestock populations.

The results shown in columns (5)–(11) of Table 7 based on Eq. (10) reveal the indirect impacts of livestock reduction on atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations. The results displayed in column (5) show that atmospheric CH_4 concentrations decreased significantly with the reduction in animal CH_4 emissions, whereas atmospheric CH_4 concentrations increased with the increase in NPP, which is in line with Keppler et al. (2006), who found that plants release CH_4. To avoid multicollinearity, we alternately added the Animal–CH_4, Animal–N_2O, and Animal–NH_3 variables, which represent animal CH_4, N_2O, and NH_3 emissions, respectively, to the regressions. The results reported in columns (6)–(11) of Table 7 show that $PM_{2.5}$ and PM_{10} concentrations decreased with the improvement in grassland quality (Wu and Tiessen, 2002; Chen et al., 2016), but $PM_{2.5}$ and PM_{10} concentrations were not significantly impacted by animal gas emissions.

6.2. Empirical evidence from rural households

Considering that changes at the county level depend on changes at the household level, we examined the effects of the GECP at the household level. We collected household data for 2020 and 2021 from 713 herders in Inner Mongolia, selected using stratified random sampling. Specifically, we selected sample counties based on three grassland types of Inner Mongolia: Sonid Right Banner (desert grassland area), West Ujimqin Banner (typical grassland area), and Ewenki Autonomous Banner and Xin Barag Left Banner (meadow grassland areas). We then selected sample villages from each county based on grassland quality. Finally, we randomly selected herders from each sample village and collected household data through face-to-face interviews. The interviews included questions about the effects of the GECP on households, such as subsidy amounts, household incomes, grassland areas, livestock populations, and farm-gate animal prices over the previous three years. After removing sample households with missing data, we obtained an unbalanced panel data set from 644 households covering the period 2018–2021.

Moreover, we calculated the animal gas emissions of each sample household based on the emission factor method (Gavrilova et al., 2019; IPCC, 2021). We adopted the emission factors used by Mei et al. (2023): different grassland types, animal feed quality, and animal ages (Tables A.4 and A.5).

Table 8
Impacts of the GECP on livestock populations and CO_2 emissions from livestock production at the household level.

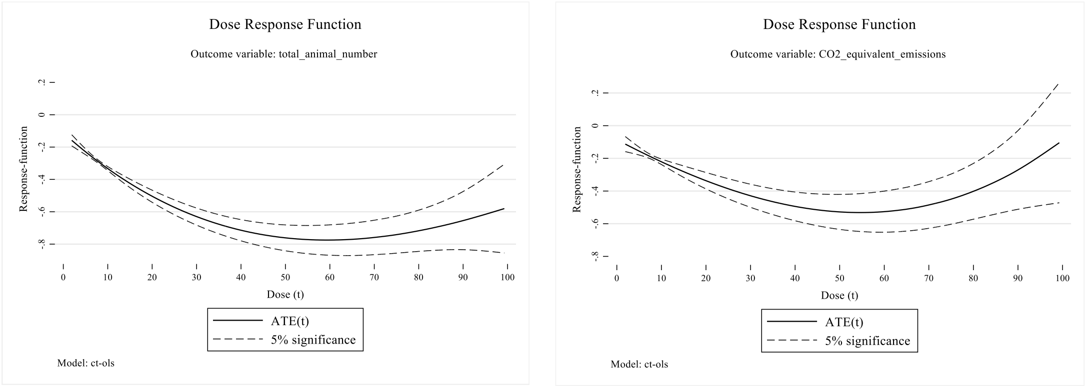
Variable	Livestock population	CO_2 emissions

	(1)	(2)	(3)	(4)
GECP	−0.831***	−0.851***	−0.389**	−0.495***
	(0.163)	(0.164)	(0.176)	(0.178)
Grassland area	0.017	0.017	−0.048	−0.009
	(0.041)	(0.041)	(0.067)	(0.053)
Weighted price	0.007	0.006	0.061***	0.035**
	(0.015)	(0.015)	(0.018)	(0.017)
Household FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
County×year FE	NO	YES	NO	YES
R^2	0.944	0.944	0.941	0.947
F	9.401	3.913	6.803	6.756
Obs.	2,110	2,110	2,110	2,110

Notes: The results in columns (1) and (3) did not control the cross terms of the county and year dummies, and the results in columns (2) and (4) controlled the cross terms. The results in columns (1) and (2) are consistent, and (3) and (4) are consistent, which indicates the results are robust. The values in parentheses are robust standard errors. ***p < 0.01, **p < 0.05.

Table 8 presents the effects of the GECP on livestock populations and CO_2 emissions at the household level based on the two-way fixed-effects model. We estimated the implementation of the GECP as the ratio of the GECP subsidy amount to the total household income. We controlled for grassland areas and cattle and sheep selling prices. We used the cross terms of the county and year dummies to control for time variance in each county. The coefficients for the GECP variable were significant and negative. The results are robust and show that the GECP reduced livestock populations and animal gas emissions at the household level, consistent with the main empirical results presented in Table 1.

The levels of exposure (or doses) to the GECP varied between households, as reflected in the subsidy amount received by each household. We used a dose–response model with "continuous" treatment to estimate the effects of the GECP under different implementation intensities as reflected in the different subsidy amounts (Cerulli, 2015). Fig. 8 presents the average treatment effects (ATE) on livestock populations and CO_2 emissions under different levels of exposure to the GECP. As shown in Fig. 8(a), livestock populations were significantly reduced at the 95% confidence level under any subsidy level. The reduction in livestock was rapid when the subsidy share was less than 60%, but the decreasing trend was slightly reversed when the subsidy amount exceeded 60%. As shown in Fig. 8(b), animal CO_2 emissions decreased rapidly before the subsidy share reached approximately 60%, after which the decreasing trend was quickly reversed. The decrease in animal CO_2 emissions was not significant at the 95% confidence level when the subsidy share exceeded approximately 90%.



a b

Fig. 8. Different impacts of the GECP on (a) animal populations and (b) carbon emissions from animals under different implementation intensities at the household level.
Note: The x-axis presents the ratio of the GECP subsidy to the total household income, and the y-axis is the ATE.

7. Discussion and conclusions

It is crucial to understand the effects of anthropogenic gas emissions on eco-environmental systems. In this study, we examined the causal effects of livestock reduction on reducing GHGs and air pollutants. To this end, we used the GECP, the largest ongoing payment-for–ecosystem services program in China intended to protect grassland ecosystems by reducing grazing livestock populations, to conduct a cross-boundary quasi-natural experimental analysis based on official statistical data, reanalysis data, remote sensing data, and household survey data. We used the state-of-the-art SDID method to examine the causal effects of the GECP on livestock populations, animal gas emissions, atmospheric CH$_4$, PM$_{2.5}$, and PM$_{10}$ concentrations, grassland quality, and carbon sequestration in grasslands.

Our empirical results showed that the implementation of the GECP caused significant reductions in livestock populations, animal CH$_4$, N$_2$O, and NH$_3$ emissions, and atmospheric CH$_4$, PM$_{2.5}$, and PM$_{10}$ concentrations and significantly increased the NDVI, NPP, and carbon sequestration in grasslands. Our pathway analysis showed that livestock reduction directly reduced animal gas emissions and increased grassland quality, which led to indirect decreases in atmospheric CH$_4$, PM$_{2.5}$, and PM$_{10}$ concentrations. Specifically, animal CH$_4$ emissions impacted atmospheric CH$_4$ concentrations, and the improvement in grassland quality reduced PM$_{2.5}$ and PM$_{10}$ concentrations, which is in line with previous natural science studies (e.g., Chen et al., 2016; Krasnov, 2016). The household-level findings are consistent with the county-level results. The GECP reduced households' animal numbers, leading to a significant reduction in animal gas emissions. The results based on the dynamic SDID method show that the reduction in livestock was greater during the second round (2016–2020) of the GECP than during the first round (2011–2015). Accordingly, the causal effects of livestock reduction on mitigating GHGs and air pollutants and enhancing grassland quality were more pronounced in the second round. Our heterogeneity analysis showed that livestock reduction was greater in counties with lower grassland quality, in which the impacts on GHGs, air pollutants, and grassland quality were also stronger. Moreover, livestock reduction was greater in counties with smaller grassland areas, in which the effects on GHGs and grassland conservation were also more pronounced, but the environmental effects on mitigating air pollution were not significant.

Our placebo tests based on a hypothetical GECP implementation in untreated areas and periods and robustness checks based on different empirical methods and observations confirmed the validity of our empirical results. Moreover, falsification tests performed to exclude possible biases related to changes in industry, local economy, and crop farming confirmed that the decreases in atmospheric CH_4, $PM_{2.5}$, and PM_{10} concentrations were caused by the reduction in livestock.

This study contributes to the current body of knowledge in several ways. First, it provides empirical evidence of the causal effects of livestock reduction on mitigating GHGs and air pollutants and reveals the related pathways. Second, it demonstrates the effects of the GECP, one of the largest grassland conservation programs in the world, on GHGs and air pollutants, which have hitherto been overlooked. Third, it demonstrates the effectiveness of SDID, a new method for making causal inferences based on panel data, which performs better in estimating causal effects than the conventional DID and SC methods. And we first introduced the dynamic SDID to extend the results of the basic SDID. Fourth, it provides a more precise estimation of the causal effects of the GECP than previous studies by innovatively using the bordering country of Mongolia as a control area in a quasi-natural experiment, since the GECP has been implemented in all pastural areas of China. Fifth, the combination of top-down satellite data and bottom-up field data from official statistical yearbooks and household surveys used to study the effects of livestock reduction on GHGs and air pollutants bridges the gap between field data (which measure ground-level GHGs and air pollutants but have poor spatial representativeness) and satellite data (which provide spatial distributions but are less representative of ground-level GHGs and air pollutants) (Cooper et al., 2022).

A few limitations of this study should be mentioned. First, the empirical results for livestock production were based exclusively on livestock populations and did not include meat output because the related data were limited, which limited us to investigate the policy impacts on productivity. Second, although N_2O is a potent greenhouse gas that can cause damage to the ozone layer, we did not evaluate its changes in the atmosphere because of data limitation. Future research should quantify and compare the effects of extensive livestock production in pastural areas and intensive livestock production in crop farming areas on GHGs and air pollutants, considering the indirect emissions related to land use for livestock and feed production.

In conclusion, we show that livestock reductions in pastural areas are beneficial not only for grassland conservation but also for reducing GHGs and air pollutants. Nevertheless, considering that the global demand for meat and milk is increasing rapidly and that the livestock sector supports about 1.3 billion producers and retailers and accounts for 40%–50% of agricultural gross domestic product (Herrero et al., 2016), caution should be exercised when arguing for a long-term and large-scale reduction in livestock to mitigate greenhouse effects and air pollution, particularly in developing countries. It has been suggested that institutions and policies could provide sufficient leverage to steer the global food system toward higher agricultural production and lesser environmental impacts (Wuepper et al., 2020a, 2020b). The experience gained from regulating carbon emissions in fossil fuel–based industries could indicate new policy paths, such as introducing animal taxes or tradeable livestock breeding permits (i.e., a livestock quota–based trading system), which are usually more efficient in terms of redistributing production resources under heterogeneous environmental and socioeconomic conditions. Market-based measures could be effective in allocating livestock production, achieving technological progress, and eventually yielding healthier outcomes by reducing GHG emissions from livestock production while ensuring animal-sourced food security. In addition to policy designs, it is feasible to limit animal gas emissions by developing emission reduction technologies, such as improving production management and feed quality or adding dietary supplements, rather than merely reducing livestock populations. Moreover, grazing accounts for 77% of global agricultural land, sustains billions of people worldwide, and is closely linked to 10 of the United Nations' 17 Sustainable Development Goals (Gregorini et al., 2022; Maestre et al., 2022). China's high-profile GECP, which is intended to achieve a balance between grazing and ecosystem protection in permanent grasslands, can serve as a valuable reference for designing policies for sustainable grassland management worldwide.

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Appendix

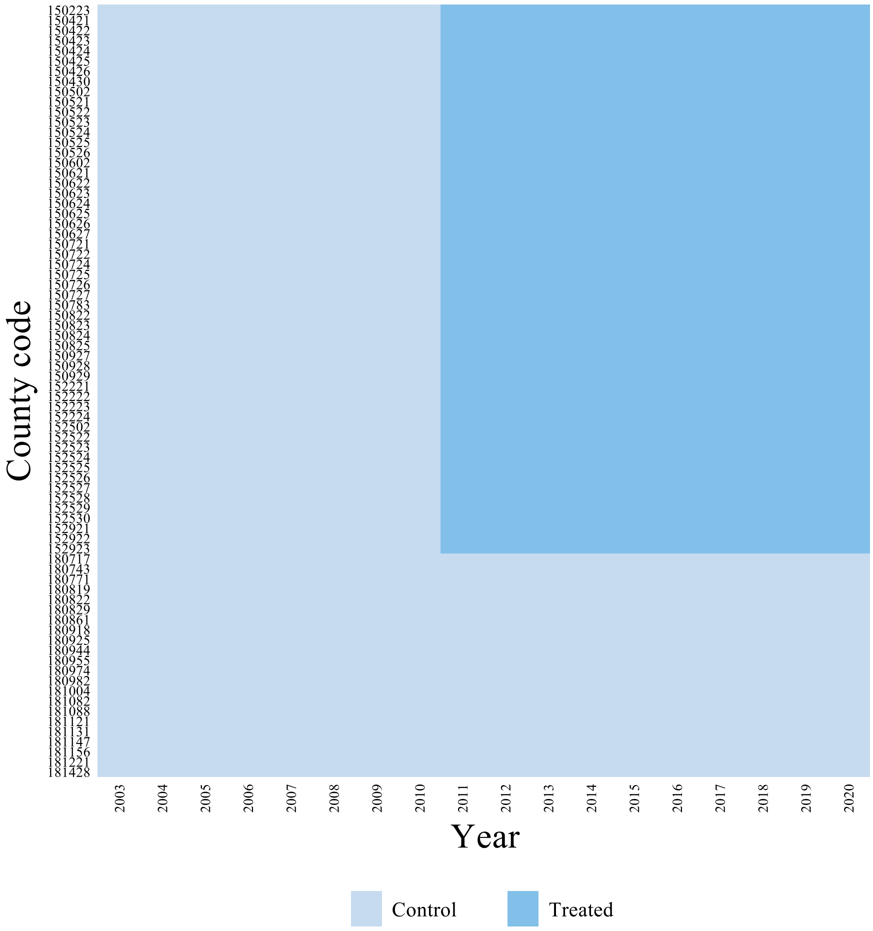


Fig. A.1. Control and treated groups in the quasi-natural experiment.

Note: The y-axis shows the Inner Mongolia and Mongolia county codes, and the x-axis shows the study years.

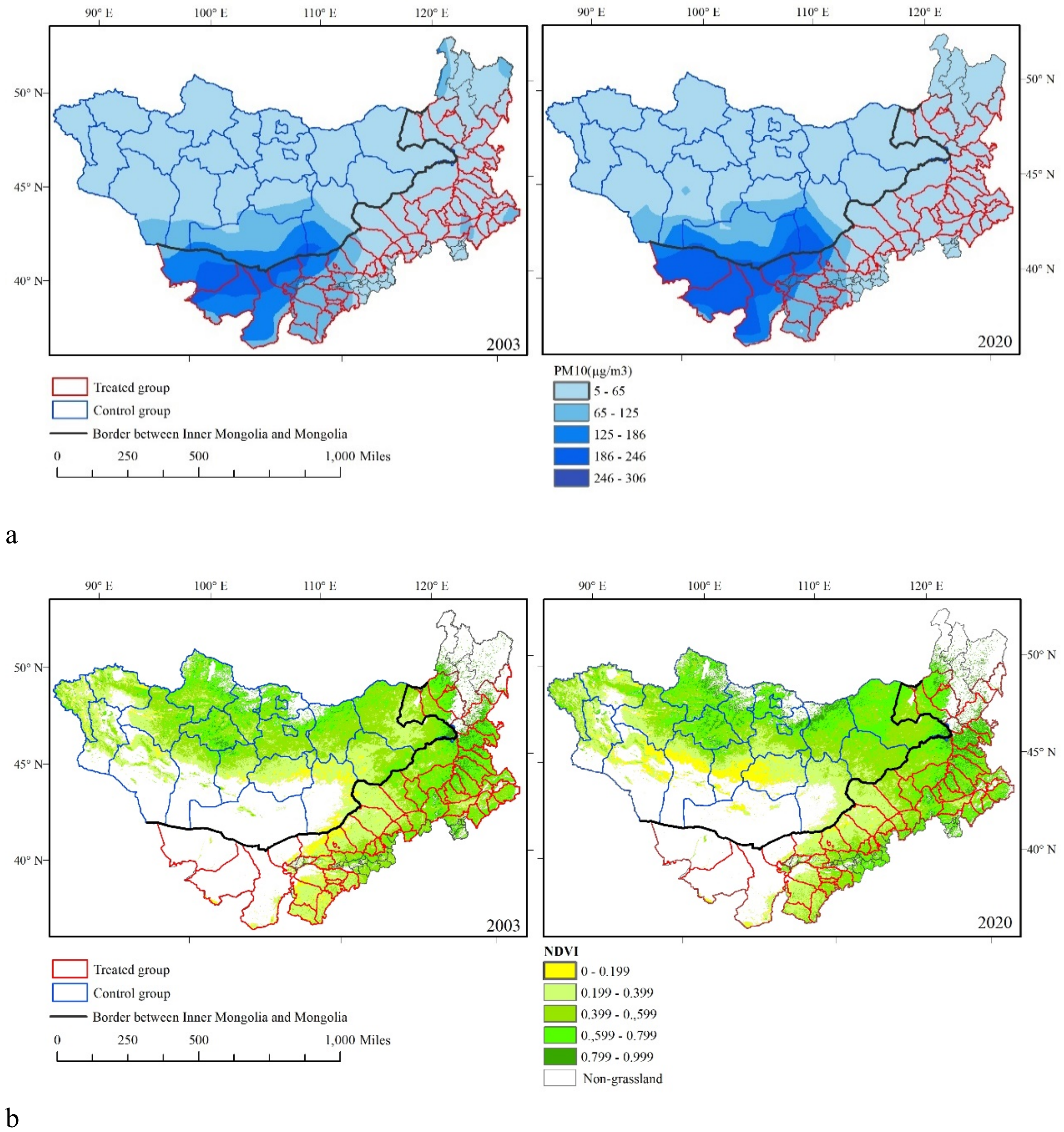


Fig. A.2. Differences in (a) PM_{10} concentrations and (b) grassland NDVI in Mongolia and Inner Mongolia between 2003 and 2020.

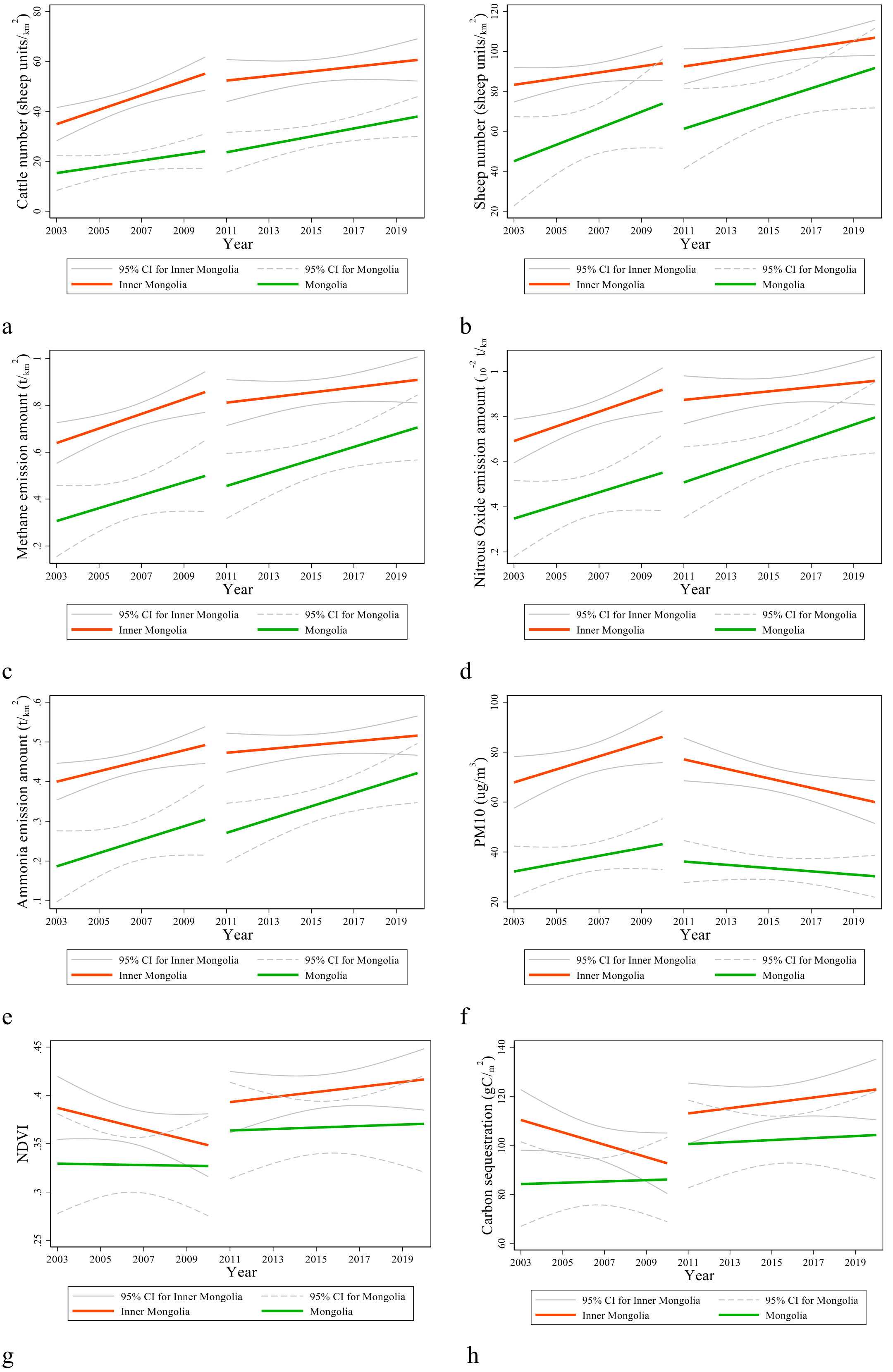
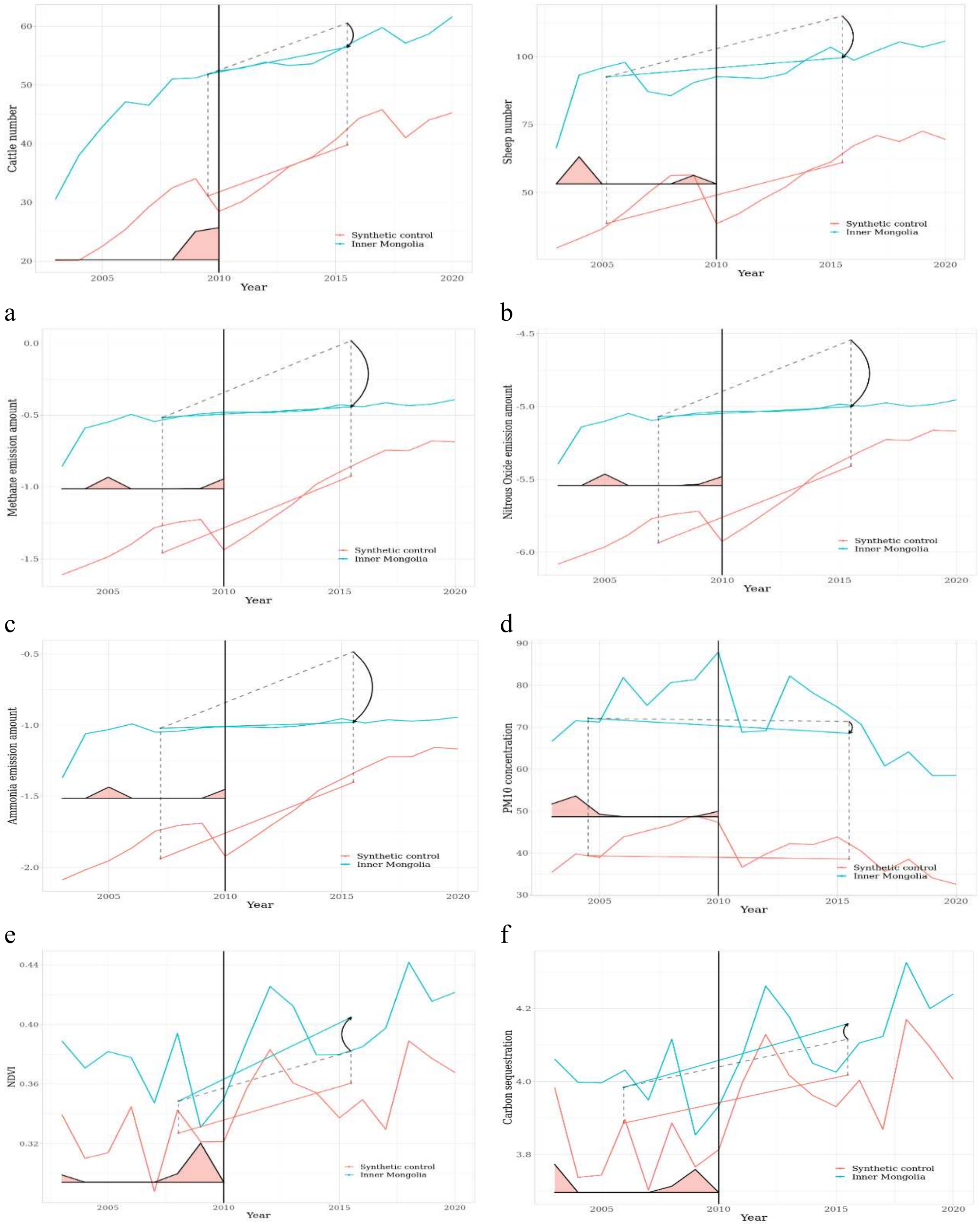


Fig. A.3. Different trends in (a) cattle and (b) sheep numbers, animal (c) CH_4, (d) N_2O, and (e) NH_3 emissions, (f) PM_{10}, (g) NDVI, and (h) carbon sequestration in grasslands in Mongolia and Inner Mongolia before and after the implementation of the GECP (2003–2020).



a b c d e f g h

Fig. A.4. Estimated causal effects of the GECP on (a) cattle and (b) sheep numbers, animal (c) CH_4, (d) N_2O, and (e) NH_3 emissions, (f) PM_{10}, (g) NDVI, and (h) carbon sequestration in grasslands based on the SDID method.

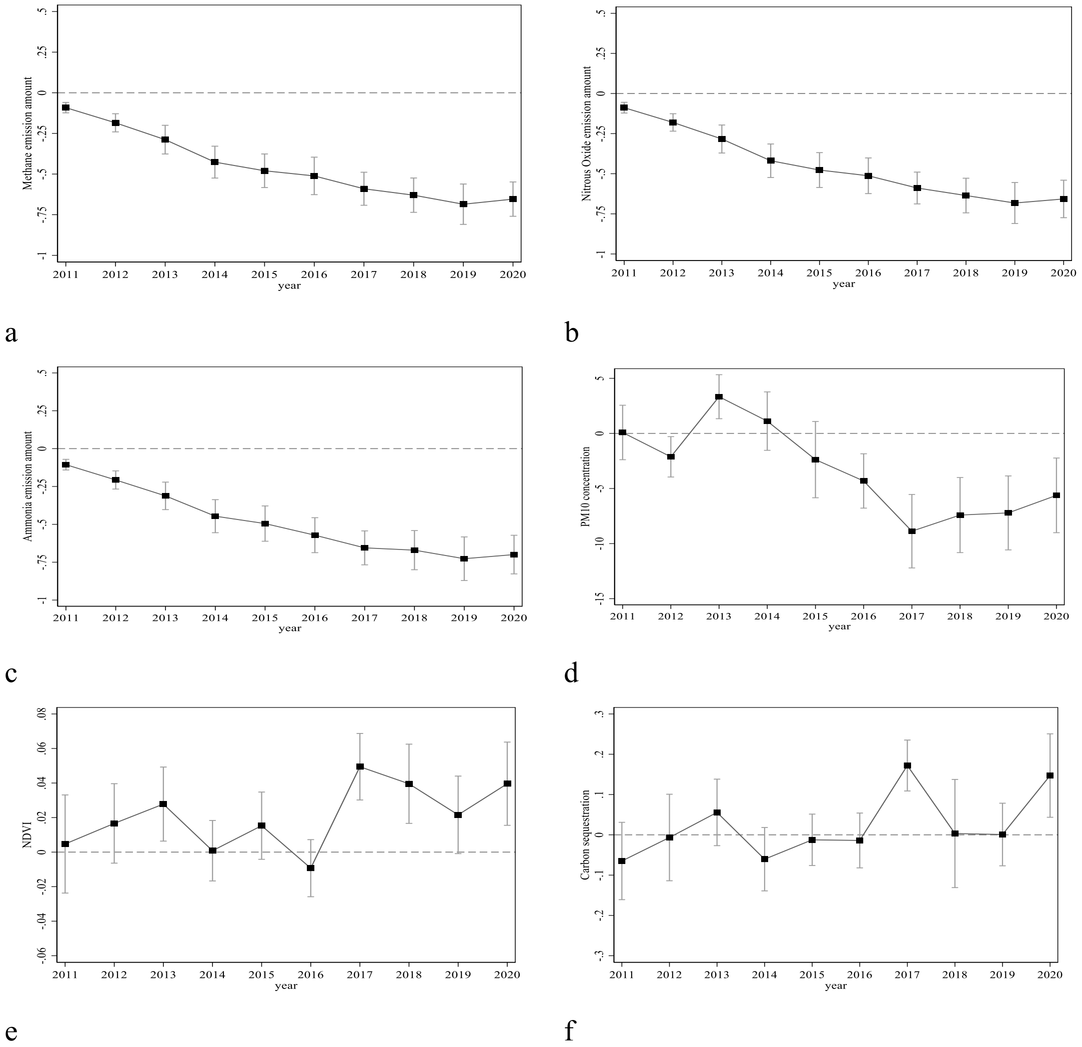


Fig. A.5. Estimated dynamic effects of the GECP on animal (a) CH_4, (b) N_2O, and (c) NH_3 emissions, (d) PM_{10}, (e) NDVI, and (f) carbon sequestration in grasslands based on the dynamic SDID method.

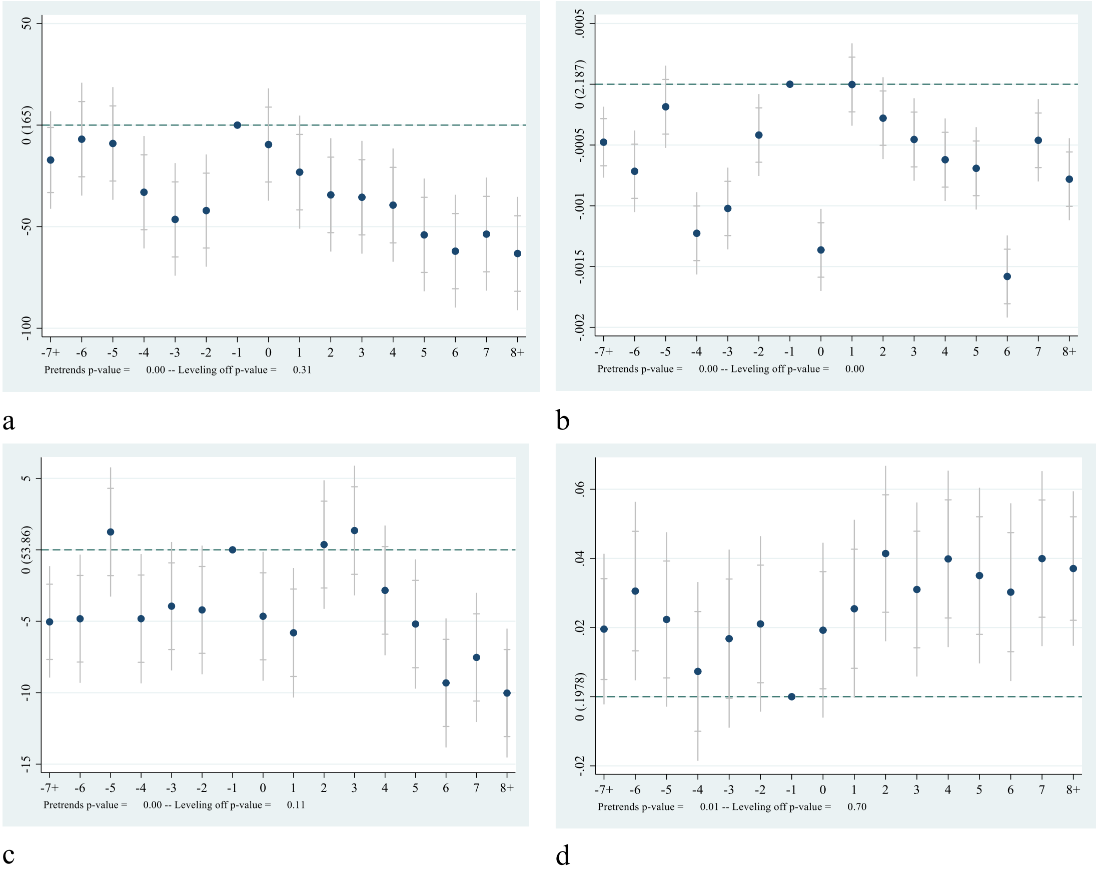


Fig. A.6. Estimated impacts of the GECP on (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP based on the event study method (with covariates).

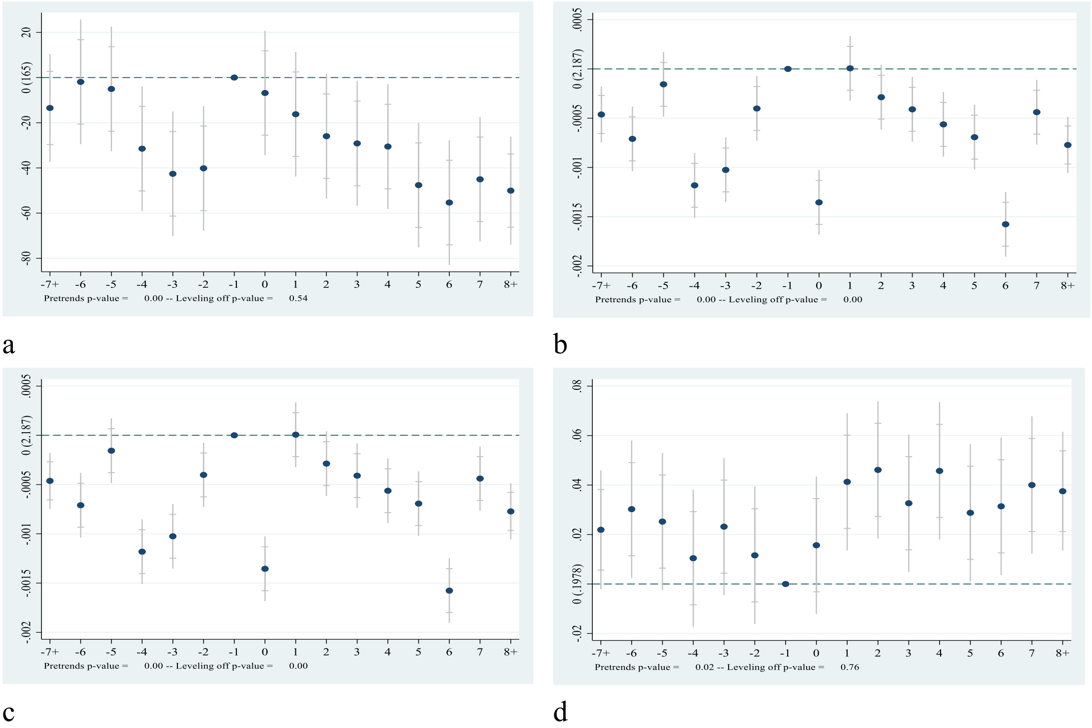


Fig. A.7. Estimated impacts of the GECP on (a) livestock populations, atmospheric (b) CH_4 and (c) $PM_{2.5}$ concentrations, and (d) grassland NPP based on the event study method (without covariates).

Table A.1

Emission factors for animal gas emissions (kg/head).

Kind of animal	Animal–CH_4		Animal–N_2O	Animal–NH_3
	Enteric fermentation (m_i)	Manure management (n_i)	Manure management (p_i)	Manure management (q_i)
Sheep	5.00	0.13	0.05	4.20
Cattle	54.00	1.35	0.58	18.60
Horse	18.00	1.09	0.36	18.60
Donkey	10.00	0.60	0.20	18.60
Mule	10.00	0.60	0.20	18.60
Camel	46.00	1.28	0.33	10.50

Note: The emission factors (m_i, n_i, p_i, and q_i) are from the IPCC guidelines (Gavrilova et al., 2019).

Table A.2

Ratios of belowground to aboveground biomass for different types of grassland.

Grassland type	Ratio
Temperate meadow steppe	5.26
Lowland meadow	6.31
Temperate steppe	4.25
Temperate steppe desert	7.89
Temperate desert	7.89

Note: The grassland types of Inner Mongolia were based on the first national grassland resource inventory of China, conducted during 1981–1988 (Piao et al., 2004). The grassland types of Mongolia were defined based on the NDVI because there were no official data. According to the relationships between the NDVI and grassland types of Inner Mongolia, grasslands with an annual maximum NDVI of less than 0.2 were considered temperate steppe deserts, grasslands with an annual maximum NDVI of more than 0.6 were considered temperate meadow steppes, and the rest were considered temperate steppes, following Wang et al.'s (2018) method.

Table A.3
Definitions and descriptive statistics of the variables used in the SDID, event study, and fixed-effects models.

Variable	Definition	Obs.	Mean
At the county level			
$Cattle_{it}$	Cattle number per square kilometer of grassland in county *i* in year *t*	1,368	44
$Sheep_{it}$	Sheep number per square kilometer of grassland in county *i* in year *t*	1,368	87
$Animal_{it}$	Total number of animals per square kilometer of grassland in county *i* in year *t*	1,368	153
$Animal - CH_{4it}$	Amount of animal CH_4 emissions per square kilometer in county *i* in year *t* (in log form)	1,368	−0.668
$Animal - N_2O_{it}$	Amount of animal N_2O emissions per square kilometer in county *i* in year *t* (in log form)	1,368	−5.205
$Animal - NH_{3it}$	Amount of animal NH_3 emissions per square kilometer in county *i* in year *t* (in log form)	1,368	−1.174
$Air - CH_{4it}$	Atmospheric CH_4 concentration in county *i* in year *t* (in log form)	1,368	2.171
$PM_{2.5it}$	Atmospheric $PM_{2.5}$ concentration in county *i* in year *t*	1,368	38.042
PM_{10it}	Atmospheric PM_{10} concentration in county *i* in year *t*	1,368	61.581
NPP_{it}	Annual grassland NPP of county *i* in year *t*	1,368	0.205
$NDVI_{it}$	Annual grassland NDVI of county *i* in year *t*	1,368	0.377
$Carbon_{it}$	Carbon sequestration in grassland in county *i* in year *t* (in log form)	1,368	4.038
$GDP2_{it}$	Gross domestic product of secondary industry in county *i* in year *t*	1,368	0.133
$Light_{it}$	Annual nighttime light intensity in county *i* in year *t*	1,368	0.054
$Cropland_{it}$	Cultivated land area in county *i* in year *t* (in log form)	1,292	3.254
$Grassland_{it}$	Grassland area in county *i* in year *t* (in log form)	1,292	9.303
Tem_{it}	Average annual temperature in county *i* in year *t*	1,368	4.125
Pre_{it}	Average annual precipitation in county *i* in year *t*	1,368	327.159
$Windangle_{it}$	Average angle of wind in county *i* in year *t*	1,368	275.066
$Windspeed_{it}$	Average annual wind speed (m/s) in county *i* in year *t*	1,368	1.609
$Drought_{it}$	Drought index of county *i* in year *t*	1,368	−0.039
$Cold_{it}$	Number of consecutive days with a temperature below −20°C over the past 14 days in county *i* in year *t*	1,368	2.817

$Price_{it}$	weight × sheep procurement price + (1 − weight) × cattle procurement price; weight = sheep number / total animal number	1,216	3.965
$Treat_i$	1 if the GECP was implemented in county *i*; 0 otherwise	1,368	0.711
$Period_t$	1 if the GECP was implemented in year *t*; 0 otherwise	1,368	0.556
At the grid level of the extended sample areas			
$Air-CH_{4_{100mt}}$	Atmospheric CH_4 concentration in the 0–100 km buffer in grid *m* in year *t* (in log form)	43,380	2.093
$PM_{2.5_{100it}}$	Atmospheric $PM_{2.5}$ concentration in the 0–100 km buffer in grid *m* in year *t*	43,380	29.297
$PM_{10_{100it}}$	Atmospheric PM_{10} concentration in the 0–100 km buffer in grid *m* in year *t*	43,380	45.974
NPP_{100it}	Annual grassland NPP in the 0–100 km buffer in grid *m* in year *t*	27,460	0.229
$NDVI_{100it}$	Annual grassland NDVI in the 0–100 km buffer in grid *m* in year *t*	27,600	0.411
$Air-CH_{4_{200mt}}$	Atmospheric CH_4 concentration in the 100–200 km buffer in grid *m* in year *t* (in log form)	48,654	2.111
$PM_{2.5_{200it}}$	Atmospheric $PM_{2.5}$ concentration in the 100–200 km buffer in grid *m* in year *t*	48,654	34.322
$PM_{10_{200it}}$	Atmospheric PM_{10} concentration in the 100–200 km buffer in grid *m* in year *t*	48,654	52.592
NPP_{200it}	Annual grassland NPP in the 100–200 km buffer in grid *m* in year *t*	30,240	0.215
$NDVI_{200it}$	Annual grassland NDVI in the 100–200 km buffer in grid *m* in year *t*	30,360	0.402
$Air-CH_{4_{300mt}}$	Atmospheric CH_4 concentration in the 200–300 km buffer in grid *m* in year *t* (in log form)	47,682	2.130
$PM_{2.5_{300it}}$	Atmospheric $PM_{2.5}$ concentration in the 200–300 km buffer in grid *m* in year *t*	47,682	41.538
$PM_{10_{300it}}$	Atmospheric PM_{10} concentration in the 200–300 km buffer in grid *m* in year *t*	47,682	62.301
NPP_{300it}	Annual grassland NPP in the 200–300 km buffer in grid *m* in year *t*	29,360	0.233
$NDVI_{300it}$	Annual grassland NDVI in the 200–300 km buffer in grid *m* in year *t*	29,400	0.433
$Air-CH_{4_{400mt}}$	Atmospheric CH_4 concentration in the 300–400 km buffer in grid *m* in year *t* (in log form)	46,260	2.139
$PM_{2.5_{400it}}$	Atmospheric $PM_{2.5}$ concentration in the 300–400 km buffer in grid *m* in year *t*	46,260	41.322
$PM_{10_{400it}}$	Atmospheric PM_{10} concentration in the 300–400 km buffer in grid *m* in year *t*	46,260	60.911
NPP_{400it}	Annual grassland NPP in the of 300–400 km buffer in grid *m* in year *t*	29,380	0.225

$NDVI_{400it}$	Annual grassland NDVI in the 300–400 km buffer in grid m in year t	29,440	0.428
At the household level			
$livestock\ population_{nt}$	Total number of animals in sheep units raised by household n in year t (in log form)	2,130	6.142
$CO_2\ emission_{nt}$	CO_2 equivalent emissions from animals for household n in year t (in log form)	2,130	11.583
$GECP_{nt}$	Ratio of GECP subsidy to the total income of household n in year t (in log form)	2,130	0.117
$grassland\ area_{nt}$	Grassland area used by household n in year t (in log form)	2,130	8.447
$weighted\ price_{nt}$	weight × sheep selling price + (1 − weight) × cattle shelling price; weight = sheep number / total animal number	2,130	8.160

Note: Data on cropland and grassland areas were not available for 2020. Therefore, the number of observations for the $Cropland_{it}$ and $Grassland_{it}$ variables was 1,292. For the drought index, $Drought_{it} = \frac{Tem_{it}-Tem_{mean}}{Tem_{sd}} - \frac{Pre_{it}-Pre_{mean}}{Pre_{sd}}$, where Tem_{mean} is the mean Tem_{it}, Tem_{sd} is the standard deviation of Tem_{it}, Pre_{mean} is the mean Pre_{it}, and Pre_{sd} is the standard deviation of Pre_{it}.

Table A.4

Emission factors for cattle calculated based on animal weights and the Tier 2 approach of the 2019 IPCC Guidelines for National Greenhouse Gas Inventories.

Gas emissions	Grassland type	Feed with low-quality forage grass		Feed with medium-quality forage grass		Feed with high-quality forage grass	
		Young cattle	Adult cattle	Young cattle	Adult cattle	Young cattle	Adult cattle
CH_4 from enteric fermentation	Desert grassland	123.76	201.71	66.49	108.37	21.54	35.12
	Typical grassland	124.34	201.74	66.80	108.38	21.65	35.13
	Meadow grassland	127.14	199.82	68.31	107.35	22.14	34.78
CH_4 from manure management	Desert grassland	3.39	5.52	1.28	2.09	0.58	0.95
	Typical grassland	3.41	5.53	1.29	2.10	0.59	0.96
	Meadow grassland	3.48	5.47	1.32	2.07	0.60	0.94
N_2O from manure management	Desert grassland	0.833	1.369	0.439	0.723	0.314	0.515
	Typical grassland	0.837	1.370	0.442	0.723	0.315	0.516
	Meadow grassland	0.856	1.356	0.452	0.716	0.322	0.510

Note: The age of cattle was determined based on each animal's weight. In the case of Chinese adult cattle (over 2 years old), the average weight is more than 400 kg. Animals with a weight less than this were considered young (Mei et al., 2022). The CH_4, N_2O, and NH_3 emissions from enteric fermentation and manure management are expressed as total CO_2 equivalent emissions.

Table A.5
Emission factors for sheep calculated based on animal weights and the Tier 2 approach of the 2019 IPCC Guidelines for National Greenhouse Gas Inventories.

Gas emissions	Grassland type	Feed with low-quality forage grass		Feed with medium-quality forage grass		Feed with high-quality forage grass	
		Young sheep	Adult sheep	Young sheep	Adult sheep	Young sheep	Adult sheep
CH_4 from enteric fermentation	Desert grassland	8.65	16.44	5.10	9.07	2.46	4.24
	Typical grassland	10.44	18.87	6.06	10.28	2.90	4.77
	Meadow grassland	9.70	18.91	5.66	10.30	2.72	4.78
CH_4 from manure management	Desert grassland	0.25	0.48	0.11	0.20	0.05	0.09
	Typical grassland	0.31	0.56	0.13	0.22	0.06	0.10
	Meadow grassland	0.28	0.56	0.12	0.22	0.05	0.10
N_2O from manure management	Desert grassland	0.055	0.105	0.033	0.058	0.024	0.042
	Typical grassland	0.066	0.120	0.039	0.064	0.029	0.048
	Meadow grassland	0.062	0.121	0.036	0.062	0.027	0.047

Note: The age of sheep was determined based on each animal's weight. In the case of Chinese adult sheep (over 1 year old), the average weight is more than 40 kg. Animals with a weight less than this were considered young (Mei et al., 2022). The CH_4, N_2O, and NH_3 emissions from enteric fermentation and manure management are expressed as total CO_2 equivalent emissions.

References in appendix

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