Contribution Isolation of LUCC Impact on Regional PM₂.₅ Air Pollution: Implications for Sustainable Land and Environment Management

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Understanding of the contribution of LUCC to air pollution is the basis for land management and air pollution control. This study aimed to estimate the contribution of LUCC to PM₂.₅ pollution levels in the Changsha-Zhuzhou-Xiangtan (CZT) urban agglomeration in the central south China. Methodologically, residual analysis was adopted to isolate the LUCC contribution with the aid of multiple datasets from satellite observations and reanalysis products. The results revealed that the PM₂.₅ concentration increased significantly from 2001 to 2008 and then decreased. LUCC tended to enhance both the increasing and decreasing trends, while the magnitudes varied under different climate conditions. During 2001–2008, LUCC exerted more important influence on the air pollution, which contributed 40.59% of the total increase. During 2008–2014, the changing climate enhanced air pollution removal. During this time, the government of the CZT proposed the "Two Oriented Society" policy for sustainable urban development. Under this condition, the LUCC accounted for only 25.66% of the total PM₂.₅ decrease. This result suggested that it is necessary to further strengthen the goal of sustainable development rather than following the traditional way of "governance after development".

Keywords: fine particulate matter, land use and cover change, multiple linear regression model, changsha-zhuzhou-xiangtan urban agglomeration, remote sensing

INTRODUCTION

The global urban area has expanded by ~ 130% in recent decades (He et al., 2019), which exerts significant impacts on the environment through changes in surface energy and the hydrologic cycle, i.e., air pollution, global and regional climate change and biodiversity reduction (Foley et al., 2005). Among them, air pollution poses a severe threat to human health (Zou et al., 2019; Zou et al., 2020), climate change (Feng and Zou 2019; Feng et al., 2019), atmospheric visibility (Wang et al., 2019) and economic development (Chen et al., 2019), which has attracted increasing attention from researchers and governments.

It is crucial to clarify the land use and cover change (LUCC) impact on air pollution for land planning and environmental management during urban growth. Physically, LUCC affects air pollution in direct and indirect ways (Feng et al., 2017). First, LUCC can directly affect the spatial distribution of emission sources (Heald and Spracklen, 2015). Second, different land

FIGURE 1 | Study area.
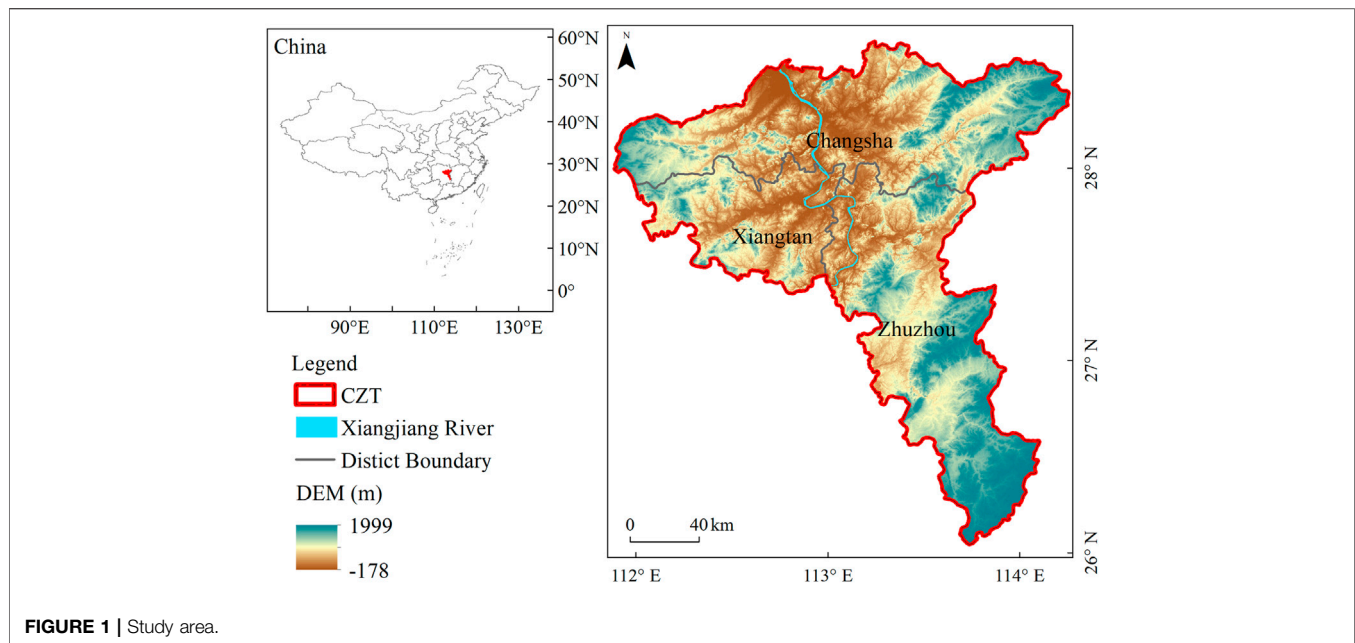
types exert various influences on dry deposition (Dzierzanowski et al., 2011). In addition, LUCC helps alter the dispersion and transportation of air pollution by changing the local or regional climate conditions (Bai et al., 2017). On the other hand, air pollution is also strongly affected by natural factors and anthropogenic emissions (Yang et al., 2018; Zheng et al., 2018). For example, precipitation controls wet deposition, which acts as one of the main removal methods of atmospheric pollutants (Ouyang et al., 2015). Wind has a direct influence on the variation in the air pollution concentration by enhancing its dispersion (Janhall 2015). Temperature and relative humidity play crucial roles in the formation of secondary aerosols by affecting the gas-to-particle process (Raes et al., 2000). Natural and anthropogenic factors affect air pollution through complex interactions, making it difficult to isolate individual effects.

Researchers have adopted several air quality models to isolate the LUCC impact by measuring the difference in air pollution with and without the influence of LUCC (i.e., WRF-Chem and GEOS-Chem) (Avise et al., 2009; Wu et al., 2012; Martin et al., 2015). However, the results are controversial due to the unavoidable uncertainty originating from the initial input, model error and prediction scenarios in different models (Bonan and Doney, 2018). For example, the modeled LUCC contribution to ozone variation ranges from −5 ppb to +5 ppb in different published works (Ganzeveld and Lelieveld, 2004; Chen et al., 2009; Squire et al., 2014). Considering these uncertainties, it has been suggested that direct observations (satellite and *in situ*) are required for accurately performing an air pollution evaluation and determining the corresponding driving factors (Bellouin et al., 2005; Seinfeld et al., 2016).

Focusing on the driving factors of air pollution, this study attempted to estimate the effect of LUCC using a statistical method with the aid of multisource satellite observations and reanalysis products. The Changsha-Zhuzhou-Xiangtan (CZT) urban agglomeration in central China, which suffers from serious air pollution of fine particulate matter ($PM_{2.5}$), was selected as the study area. First, the spatial-temporal variations in the annual $PM_{2.5}$ concentration were analyzed during the last decade (2001–2014). Then, residual analysis of the MLR model was performed to isolate the influence of LUCC on $PM_{2.5}$. The results of this study will help capture the characteristics of air pollution evolution and provide valuable information for improving urban air quality by optimizing land management strategies.

METHODS

Study Area

The Changsha-Zhuzhou-Xiangtan (CZT) urban agglomeration, which spans 111°53′E to 114°15′E longitude and 23°2′N to 28°39′N latitude, was selected as the study area for this investigation. The study area is located in northeast Hunan Province, China, and includes the cities of Changsha, Zhuzhou and Xiangtan (**Figure 1**). The climate of the CZT is characterized by the subtropical humid monsoon with abundant precipitation and warm temperatures. The center of the CZT is at a low altitude and is surrounded by mountains, resulting in unfavorable diffusion conditions. As one of the regions with the fastest economic development and urbanization in midwest China, the study area has experienced severe atmospheric environmental problems. Considering the serious air pollution in the CZT, this area was designated one of the thirteen priority areas for air pollution control according to the National Plan on Air Pollution Control by the Chinese government during the 12th Five-Year Plan (2011–2015) (Chen et al., 2013).

Data Sources and Preprocessing

According to our previous study (Feng and Zou, 2020), the variation in air pollution is controlled by natural and anthropogenic factors. Natural factors mainly refer to meteorological or natural surface parameters, including precipitation, surface and air temperatures, surface wind speed, relative humidity and terrain. Anthropogenic factors are strongly represented by human activities, such as anthropogenic emissions and land use and cover change (LUCC) (Feng and Zou, 2019). These datasets were also adopted to carry out the investigation in this study. Multi-source data sets have different spatial and temporal scales, which must be uniform before the investigation. Thus, All the datasets were resampled to the same spatial resolution (0.01°) through the NEAREST interpolation method and temporal scale (annual).

1) **$PM_{2.5}$ concentration.** The annual surface $PM_{2.5}$ concentration, at a resolution of 0.01°, was collected from the Atmospheric Composition Analysis Group (http://fizz.phys.dal.ca/~atmos/martin/). The data were estimated by combining aerosol optical depth (AOD) retrievals from MODIS, MISR, and SeaWIFS with the GEOS-Chen chemical transport model. The annual mean $PM_{2.5}$ estimate from this dataset was highly consistent with global ground observations ($R^2 = 0.81$; slope = 0.90). This study used the China regional datasets of V4.CH.03 from 2001 to 2014, which are widely used in national- and regional-scale research (van Donkelaar et al., 2019; Shi et al., 2020; Yue et al., 2020).

2) **Natural parameter datasets.** Natural parameter data were used to investigate the natural factors of air pollution, including precipitation, surface and air temperatures, wind speed, relative humidity and terrain. Integrated Multi-Satellite Retrievals for Global Precipitation Mission (IMERG) monthly precipitation data at a resolution of 0.1° were downloaded from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) (https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGM_V06/summary). The data showed the best expression of precipitation, with a correlation of 0.79 (Yu et al., 2020). The land surface temperature of MODIS/Terra Land Surface Temperature/Emissivity Monthly L3 Global 0.05Deg CMG (MOD11C3) (https://lpdaac.usgs.gov/products/mod11c3v006/) at a resolution of 0.05° was selected over the time period of 2001–2014. The annually averaged air temperature and wind speed data from the China Meteorological Forcing Dataset (CMFD) were downloaded from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/zh-hans/data/8028b944-daaa-4511-8769-965612652c49/), which were produced by merging a variety of data sources (He et al., 2020a). The relative humidity data at a resolution of 0.1° were collected from the Copernicus Climate Change Service (C3S) Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab = overview). In addition to the atmospheric data, terrain DEM data were adopted; these data were available from the ASTER GDEM at a resolution of 30 m collected from the Geospatial Data Cloud (http://www.gscloud.cn).

3) **Anthropogenic factors datasets.** In addition to the natural parameter data, land use and cover data and anthropogenic emissions inventories were used to investigate the anthropogenic drivers of air pollution. Specifically, land use data at a 1 km resolution in 2000, 2005, 2010, and 2015 from the Resource and Environment Science and Data Center, Chinese Academy of Science (http://www.resdc.cn), were reclassified into classes of built-up, forest, grassland, water, agricultural land, and bare soil. The land use data were generated by artificial visual interpretation from Landsat TM/ETM remote sensing images, and the overall accuracy was above 91.20% (Liu et al., 2014). Anthropogenic emissions inventories of $PM_{2.5}$ with a spatial resolution of 0.1° were obtained from the Peking University website (http://inventory.pku.edu.cn/).

Methodology

Considering the unavoidable uncertainty of the model, this study used the statistical method of residual analysis to estimate the LUCC impact. The method has been applied in several studies and has shown great potential for identifying and clarifying the driving factors of environmental change (Tai et al., 2010; Che et al., 2019; Li et al., 2019; He et al., 2020b). Methodologically, the trend of observed $PM_{2.5}$ was used to present the actual change in air pollution. Then, the theoretical $PM_{2.5}$ concentration without LUCC impact was simulated by a stepwise MLR model. Finally, the residual trend between the observed and theoretical $PM_{2.5}$ trends was adopted to represent the LUCC influence.

For each grid, the theoretical $PM_{2.5}$ concentration estimated by the MLR model can be written as:

$$P_{mod} = f(P, T_a, T_s, WS, RH, DEM, EMI) \qquad (1)$$

where P_{mod} is the $PM_{2.5}$ concentration under the control of factors other than land use, P, Ta, Ts, WS, RH, DEM and EMI represent the explanatory variables of precipitation, air temperature, land surface temperature, wind speed, relative humidity, terrain and anthropogenic emissions, respectively.

Because the MLR model does not consider the LUCC impact, a residual exists between the observed and MLR-simulated $PM_{2.5}$ concentrations, which reflects the land use influence. The residual is calculated by the following equation:
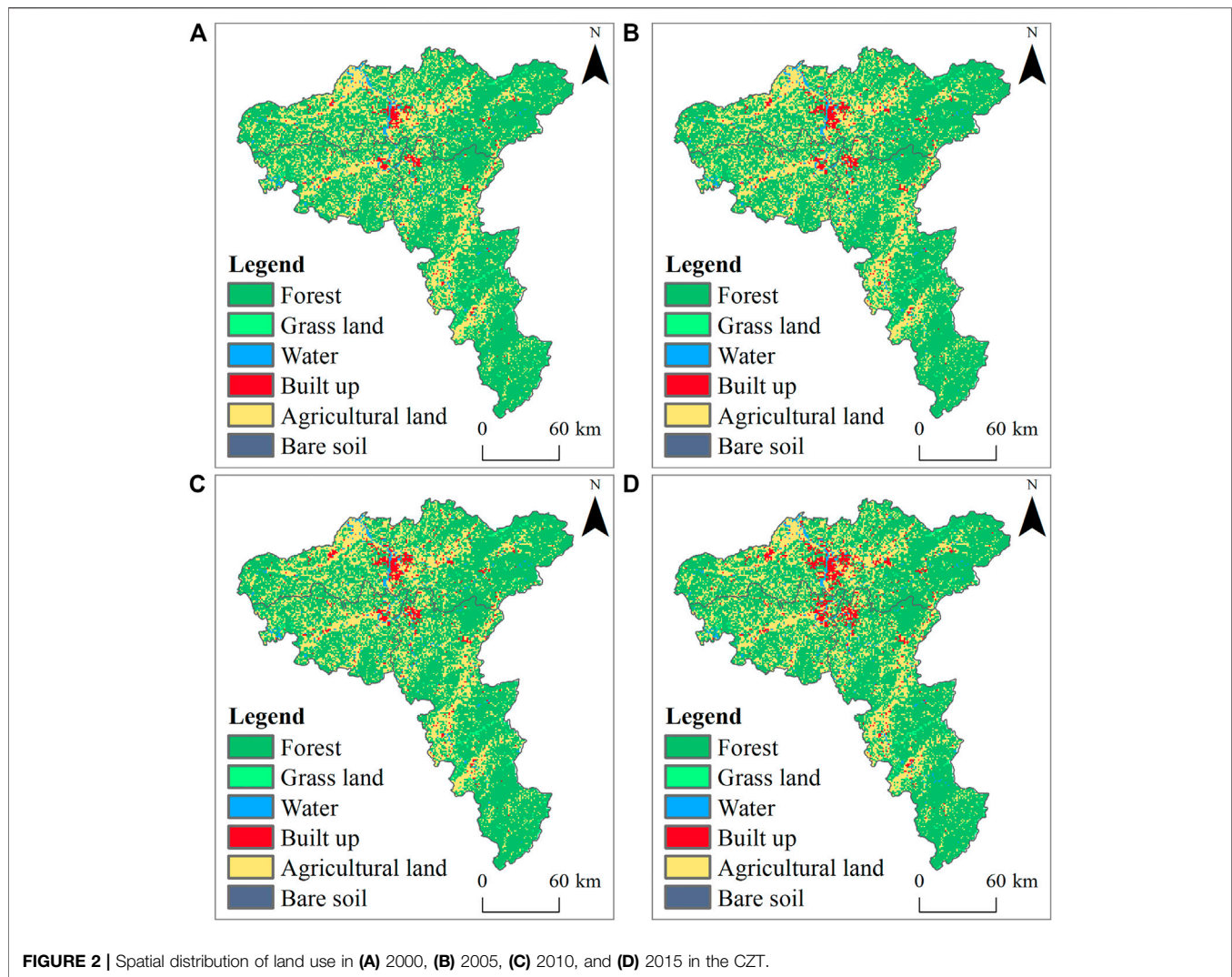
$$residual = P_{obs} - P_{mod} \qquad (2)$$

where $residual$ is the residual of the MLR model, P_{obs} represents the observed $PM_{2.5}$ concentration, and P_{mod} is the MLR simulated $PM_{2.5}$ concentration.

The trends of the observed $PM_{2.5}$ concentration and the residual represent the actual variation and the LUCC impact of the $PM_{2.5}$ concentration. We then estimate the relative contribution of LUCC as:

$$C = \frac{T_{res}}{T_{obs}} \times 100\% \qquad (3)$$

where C is the relative contribution of LUCC to the $PM_{2.5}$ concentration variation, T_{res} represents the trend of the residual, and T_{obs} is the trend of the observed $PM_{2.5}$ concentration.

FIGURE 2 | Spatial distribution of land use in **(A)** 2000, **(B)** 2005, **(C)** 2010, and **(D)** 2015 in the CZT.

TABLE 1 | Area percentage statistics of land use types.

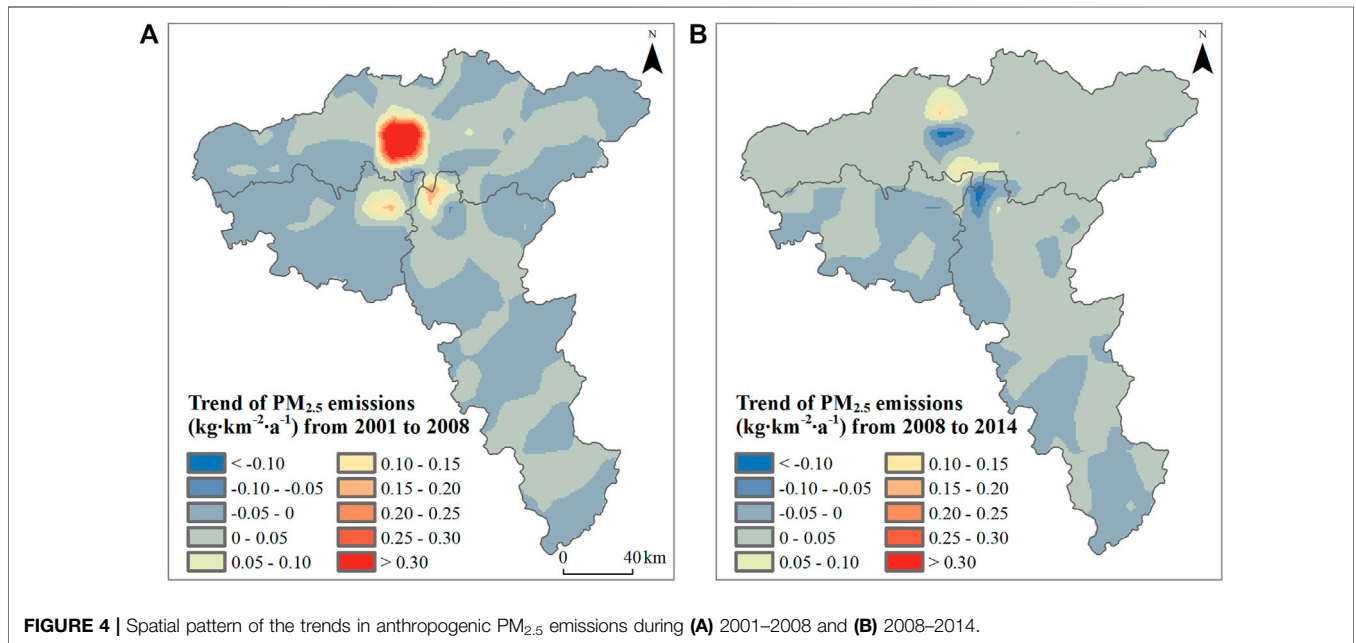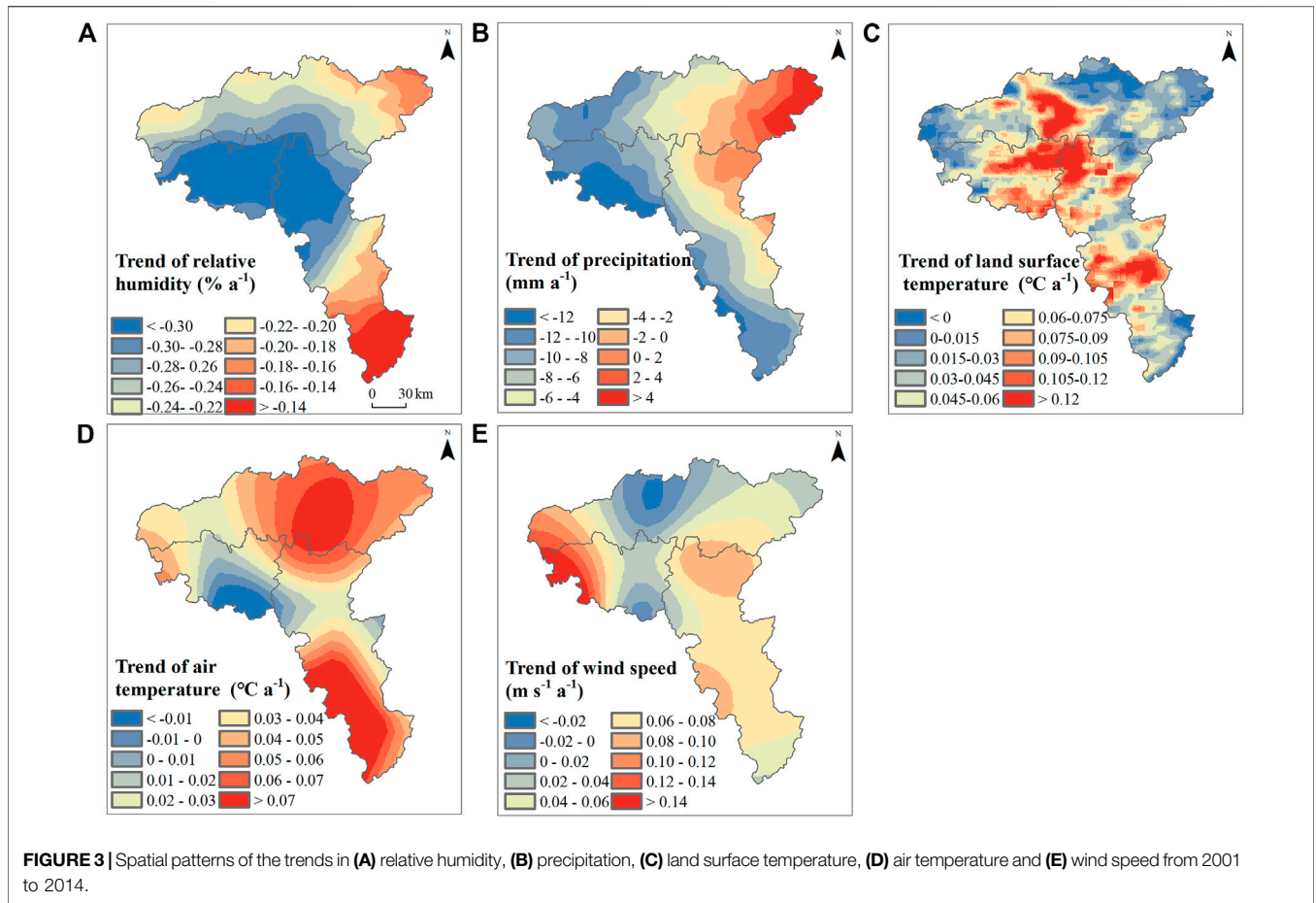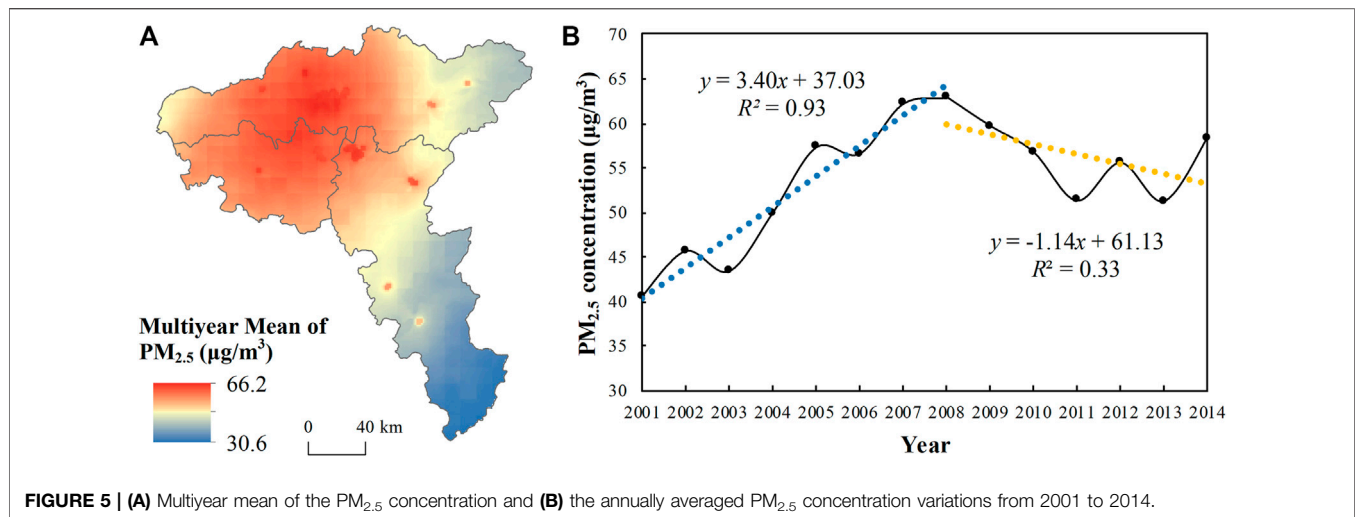| Land use type	2000 (%)	2005 (%)	2010 (%)	2015 (%)
Agricultural land	30.59	30.31	30.13	29.41
Forest	63.80	63.56	63.43	63.03
Grass land	1.46	1.45	1.45	1.43
Water	1.87	1.89	1.91	1.96
Built-up	2.27	2.78	3.07	4.16
Bare soil	0.01	0.01	0.01	0.01

RESULTS AND DISCUSSION

Spatial Pattern and Temporal Trend of LUCC, Meteorological Conditions and Anthropogenic Emissions in the CZT

It is necessary to first capture the spatial and temporal trends of LUCC, climate and anthropogenic emissions to understand the mechanism of air pollution in the CZT. The distributions of land use in 2000, 2005, 2010, and 2015 are presented in **Figure 2** and **Table 1**. Generally, forest (63.46%) is the dominant land use type in the CZT, followed by agricultural land (30.11%) and built-up land (3.07%). Spatially, forests are mainly distributed in the west, east and south of the urban agglomeration at a high altitude. urban are located mainly along the Xiangjiang River, and agricultural land is distributed around the built-up areas. Since China implemented the reform and opening up policy in 1978, urban sprawl and industrial development in the CZT have been increasingly occupying forest and farmland. The proportion of built-up areas increased from 637.57 km^2 in 2000 to 1168.42 km^2 in 2015. The expansion of built-up areas is mainly from the conversion of agricultural land and forest, whose areas were reduced to 331.43 and 216.27 km^2, respectively. The water area increased slightly (from 1.87 to 1.96%). In addition, grassland decreased from 1.46 to 1.43%.

Figures 3, **4** present the spatial patterns of the temporal trends of the meteorological factors and anthropogenic emission. The relative humidity decreased in the central CZT and slightly increased in southern Zhuzhou. The rising trend of

FIGURE 3 | Spatial patterns of the trends in (A) relative humidity, (B) precipitation, (C) land surface temperature, (D) air temperature and (E) wind speed from 2001 to 2014.

FIGURE 4 | Spatial pattern of the trends in anthropogenic PM$_{2.5}$ emissions during (A) 2001–2008 and (B) 2008–2014.

FIGURE 5 | (A) Multiyear mean of the PM$_{2.5}$ concentration and **(B)** the annually averaged PM$_{2.5}$ concentration variations from 2001 to 2014.

precipitation gradually weakened from east to west and showed a decreasing trend in the west. Because of the urban heat island effect, the land surface temperature increased in both urban and suburban areas. Air temperature dropped in the western CZT, while it increased in eastern Changsha and southern Zhuzhou. Wind speed presented a significantly increasing trend in the entire CZT, with the greatest increase occurring in the western region. Some studies also found the recovery of surface wind speed from stilling (Kim and Paik 2015; Li et al., 2018; Zeng et al., 2019). During the 2001–2008 period, anthropogenic emissions increased significantly in urban areas of the central CZT. From 2008 to 2014, emissions in Changsha and Zhuzhou urban areas decreased, while other areas changed slightly.

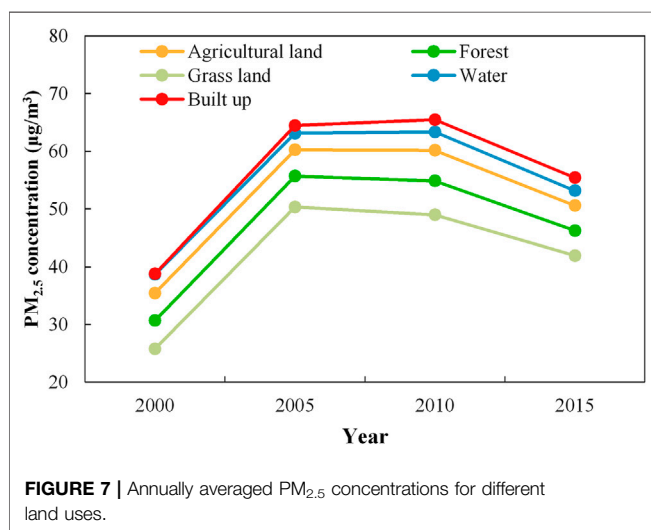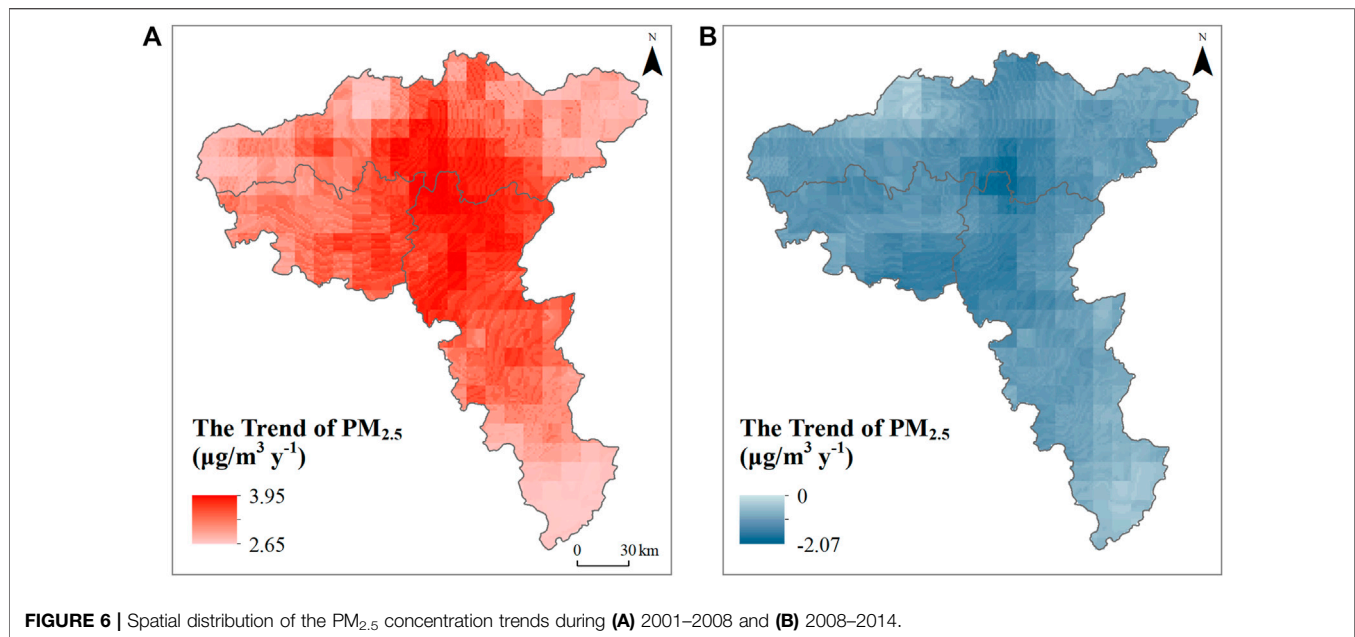## Spatial-Temporal Characteristics of PM$_{2.5}$ Concentrations

Under the background of regional LUCC, air pollution was characterized by significant spatial and temporal variations in the CZT (**Figure 5**). Generally, the multiyear mean of the PM$_{2.5}$ concentrations was 53.71 μg/m^3, with the spatial distribution mainly characterized as high in the west and north and low in the east and south (**Figure 5A**). At the scale of land use types, the PM$_{2.5}$ concentrations are high in urban areas and relatively low in rural and suburban areas, which is consistent with most of the previous studies (Zou et al., 2016; Liu et al., 2020). Specifically, the most polluted districts were central Changsha, northeastern Xiangtan and northwestern Zhuzhou, while the areas with the best air quality were eastern Changsha and southern Zhuzhou. **Figure 5B** shows the temporal changes in the PM$_{2.5}$ concentrations, which present a significant peak pattern. During the 2001–2008 period, the PM$_{2.5}$ concentrations increased significantly by 3.40 μg m^{-3}·a^{-1} (R^2 = 0.93, p < 0.05). During the period 2008–2014, however, the PM$_{2.5}$ concentrations decreased by −1.14 μg m^{-3}·a^{-1} (R^2 = 0.33, p = 0.18). The decreasing trend of the PM$_{2.5}$ concentration starting from 2008 resulted because the CZT became one of the

areas that implemented the "Two Oriented Society" policy in 2007. To build a resource-saving and environmentally friendly society, local governments have adopted a series of policies of land management and air pollution mitigation, including encouraging high-tech industries with clean production to replace traditional industries, afforesting waste hills or unclaimed lands, and building greenbelts along streets. Moreover, the original disordered productive land use has gradually been replaced by science parks (Zou et al., 2016).

Figure 6 further shows the spatial distribution of the PM$_{2.5}$ concentration trends during the periods 2001–2008 and 2008–2014. From 2001 to 2008, the PM$_{2.5}$ concentrations increased over the entire CZT. The worsening air pollution was mainly found in northern Zhuzhou, where the PM$_{2.5}$ concentration was relatively low. With respect to the period 2008–2014, the PM$_{2.5}$ concentration showed a significant reduction over the entire study area. The largest decreasing trend occurred in the central regions, where PM$_{2.5}$ pollution was relatively severe. Despite great improvement, the study area still faced serious air pollution in 2014, with 96.62% of the area still greatly exceeding the Chinese National Ambient Air Quality Standards (CNAAQS, i.e., Level-2, 35 μg/m^3). Strict controlling policies need to be continued in the future.

Impact of LUCC on PM$_{2.5}$ Evolution

This study next explores the LUCC impact on PM$_{2.5}$ for land and environmental management. **Figure 7** shows the annually averaged PM$_{2.5}$ concentrations for five land use types in 2000, 2005, 2010, and 2015. From 2000 to 2005, the annual mean PM$_{2.5}$ concentrations for all land use types greatly increased. The magnitude of the increase was highest in built-up areas. This increase may be because urban land concentrates high anthropogenic emissions, such as automobile exhaust and industrial activities. Notably, the PM$_{2.5}$ concentrations in the water body and farmland use types were also relatively high. The water body land use type is mainly distributed in urban and suburban areas. Thus, particles from the built-up area are transmitted to water areas with low altitudes through

FIGURE 6 | Spatial distribution of the PM$_{2.5}$ concentration trends during **(A)** 2001–2008 and **(B)** 2008–2014.

FIGURE 7 | Annually averaged PM$_{2.5}$ concentrations for different land uses.

diffusion, resulting in a higher PM$_{2.5}$ concentration. Agricultural waste burning and clearing, including open field burning and burning as household fuel, are significant emission sources of PM$_{2.5}$ (Zhang et al., 2017). In contrast, the PM$_{2.5}$ concentrations in forests and grasslands were relatively low, indicating that these land types could promote a decrease in the PM$_{2.5}$ concentration through the deposition effect and stomatal absorption from the vegetation blade surface (Nowak et al., 2013; Reddington et al., 2015). Correlations between air pollution and natural factors were also evaluated (see **Supplementary Figure S1**). Specifically, the PM$_{2.5}$ concentration showed negative correlations with relative humidity, precipitation and wind speed. Conversely, both air temperature and land surface temperature showed positive correlations with the PM$_{2.5}$ concentration.

To quantify the LUCC influence, the MLR model was used to simulate the PM$_{2.5}$ concentrations under the control of other factors (factors except for land use). **Figure 8** shows the trends of the MLR-simulated PM$_{2.5}$ concentrations and the residual during the periods 2001–2008 and 2008–2014, which present similar trends with the observed PM$_{2.5}$. Specifically, the simulated PM$_{2.5}$ concentration and the residual increased by 2.02 µg m^{-3}·a^{-1} ($R^2 = 0.96$, $p < 0.05$) and 1.37 µg m^{-3}·a^{-1} ($R^2 = 0.76$, $p < 0.05$) during 2001–2008. As a result, the relative contributions of the LUCC and other factors were 40.59 and 59.41%, indicating the predominant factors of emissions and meteorological conditions for the worsening air quality. During 2008–2014, the observed PM$_{2.5}$ concentration decreased by -1.13 µg m^{-3}·a^{-1}, while the simulated PM$_{2.5}$ concentration and residual decreased by -0.85 µg m^{-3}·a^{-1} ($R^2 = 0.46$, $p = 0.09$) and -0.29 µg m^{-3}·a^{-1} ($R^2 = 0.13$, $p = 0.43$). The relative contributions of land use and other factors were therefore 25.66 and 74.34%, suggesting the increasing influences of climate factors and anthropogenic emission. The main reason might be attributed to the strengthening influence of the climate conditions. As shown in **Supplementary Figure S3**, the meteorological conditions changed significantly after 2008, characterized by increased humidity, precipitation, and wind speed and decreased land surface temperature. Under these conditions, the climate tends to mitigate air pollution effectively. Our results are similar to Zhang et al. (2020), which implemented sensitivity experiments based on atmospheric chemistry model and demonstrated that contribution of more favorable meteorological conditions on decrease in PM$_{2.5}$ were higher than emission in Beijing. In conclusion, the signs of the LUCC impact remain positive, suggesting that land activities promote air pollution evolution. On the other hand, the magnitude is much greater in the process of the
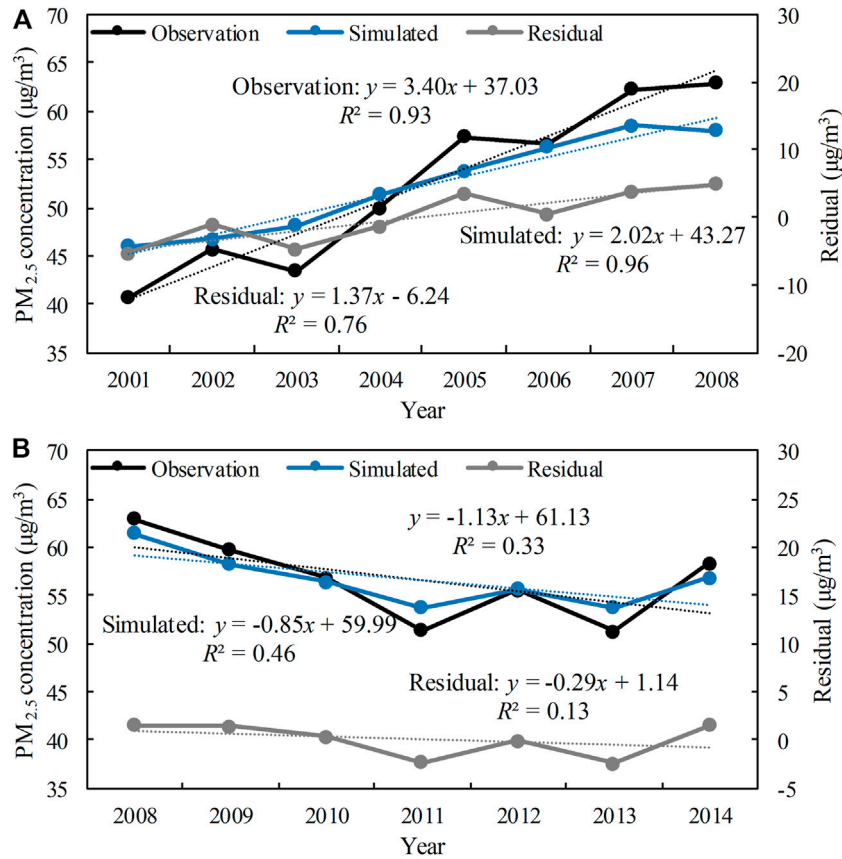
FIGURE 8 | Temporal trends of the observed, MLR simulated, and residual PM$_{2.5}$ concentrations during the periods **(A)** 2001–2008 and **(B)** 2008–2014.
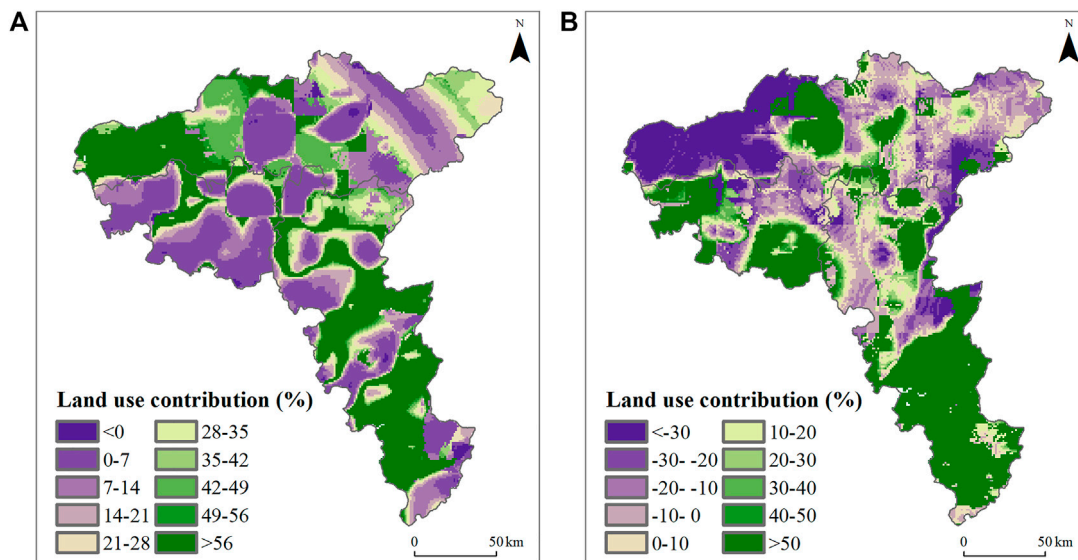
FIGURE 9 | Pixelwise contributions of LUCC impact during the period **(A)** 2001–2008 and **(B)** 2008–2014.

increase in $PM_{2.5}$, suggesting that the costs of unreasonable land activities are much higher than the benefits of rational land policy. Therefore, strengthening sustainable land management rather than following the traditional way of "governance after development" is required.

Figure 9 further shows the pixelwise contributions of the LUCC impact. From 2001 to 2008, the influences of natural factors and emissions were relatively large in urban areas. In contrast, land use acted as the primary contributor in western Changsha and southern Zhuzhou. During 2008–2014, the decreasing trend of the $PM_{2.5}$ concentration was also mainly controlled by natural factors and anthropogenic emissions, with most of the LUCC contributions less than 50%. The land use-dominant areas were located in southern Xiangtan, the urban area of Changsha and southern Zhuzhou. Additionally, LUCC weakened the decreasing trend in the suburbs located in western Changsha, which might be attributed to the increase of built-up areas and the decrease of vegetation coverage during the rapid urbanization after 2008 (**Figure 2** and **Supplementary Figure S4**).

CONCLUSION

This study aimed to explore the impact of LUCC on $PM_{2.5}$ pollution levels in the CZT from 2000 to 2014. Residual analysis of the MLR model was adopted with the aid of multiple source datasets (including satellites and reanalysis). The main conclusions are as follows:

Because of the implementation of the Two-Orientated Society policy since 2007, there was a turning point of air pollution evolution after 2008 in the CZT. Specifically, the $PM_{2.5}$ concentration increased significantly by 3.40 µg m^{-3}·a^{-1} ($R^2 = 0.93$, $p < 0.05$) from 2001 to 2008 and then decreased by -1.14 µg m^{-3}·a^{-1} ($R^2 = 0.33$, $p = 0.18$) after 2008. However, the study area still suffered from serious air pollution, which requires sustained efforts from environmental management.

LUCC exhibited a strong influence on air pollution. The statistical results show that the $PM_{2.5}$ concentrations were high in built-up, water body and farmland land use types, while they were relatively low in forest and grassland land use types. The correlations between air pollution and climate were relatively complex. The $PM_{2.5}$ concentration had negative correlations with relative humidity, precipitation and wind speed and positive correlations with air temperature and land surface temperature. However, the weak correlation ($p > 0.05$) between the $PM_{2.5}$ concentration and individual meteorological parameters suggests that it is difficult for individual factors to explain the $PM_{2.5}$ concentration variation.

With the MLR model, the LUCC influence was finally estimated. From 2001 to 2008, LUCC accounted for 40.59% of the increase. During 2008–2014, the meteorological conditions changed, significantly enhancing the air pollution cleaning ability, which was characterized by increased humidity, precipitation and wind speed and decreased land surface temperature. Under this condition, the natural and emissions contributions (74.34%) were much greater than the contribution of LUCC (25.66%). This result suggested that the negative impact of unreasonable land management was much stronger than the positive impact of sustainable land development. Therefore, it is necessary to further strengthen the goal of sustainable development in regional land and environment management rather than following the traditional way of "governance after development". Furthermore, the LUCC impact presented significant spatial variabilities. From 2001 to 2008, LUCC significantly worsened the air quality in western Changsha and southern Zhuzhou. During 2008–2014, the $PM_{2.5}$ concentration variation was mainly controlled by natural factors and emissions, and land use-dominant areas were only located in southern Xiangtan, the urban area of Changsha and southern Zhuzhou.

This study clarified the impact of LUCC on air pollution, which could help capture the driving factors of air pollution and support sustainable land planning. Several issues should be addressed in future research. First, the physical mechanism of the LUCC impact should be fully investigated to understand its influences. Furthermore, natural factors and anthropogenic factors exert significant interactions under the complex system of Earth, which will require further evaluation to capture the sign and magnitude of the LUCC impacts.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YD: Data curation, Software, Visualization, Writing-Original draft preparation. HF: Conceptualization, Methodology, Supervision, Editing. BZ: Investigation and Reviewing. SY: Editing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.825732/full#supplementary-material

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