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Evaluation and Implication of the Policies towards China's Carbon Neutrality

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Abstract: China announced it will achieve a carbon emission peak by 2030 and carbon neutrality by 2060 to fulfill its international obligations and mitigate climate risk. Related activities and polices were introduced in several sectors before this announcement. The performance and outcome of these activities provide necessary a priori knowledge for the designation and optimization of future policies. In this study, a comprehensive evaluation covering major sectors based on multisource data is proposed. The results show that although China is the largest CO_2 emitter for the current stage, the increasing rate of carbon emissions has been significantly mitigated since the 2010s. This reduction in emissions can be accelerated by the carbon-trading scheme in pilot regions. As a substitution for fossil energy, there have been tens of thousands of increases in wind turbines and photovoltaic plants in the past decade. Additionally, an enhancement of the terrestrial carbon sink was detected by time-series remote sensing data. The results of this study demonstrate that China's carbon activities in the past decade have received reasonable outcomes, which will benefit the optimization of related government policies. The improved legislation and policies of China can strengthen the regulation of emissions while promoting the quantity and quality of carbon sinks. At the same time, the improvement of the carbon emissions trading mechanism, especially the establishment of a marketing regulation mechanism, can significantly motivate interest-related communities and industries to abort high-carbon emissions and ensure the implementation of carbon neutrality in the future.

Keywords: carbon neutrality; carbon emission; carbon sink; environmental law; remote sensing

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1. Introduction

Increasing atmospheric greenhouse gases (GHGs), especially those caused by anthropogenic activities from the beginning of the industrial era, are leading to a warming climate [1]. Together, these two trends also accelerate terrestrial and aquatic processes that are harmful to human beings, such as glacier retreat [2], increased drought frequency [3], and reduced local agricultural productivity [4]. A total of 178 countries worldwide have signed the Paris Agreement to limit the rise of global average temperature to well below 2 °C and preferably to 1.5 °C compared to preindustrial levels, performing a new task to reduce the emission of GHGs, especially CO_2, since it has the largest contribution to warming in recent decades compared to other GHGs such as methane [5]. Due to rapid industrialization and urbanization, China has become the largest carbon emitter in the world since the 2000s, accounting for ~28% of global CO_2 emissions [6,7]. Additionally, China contributes more than 10% of global anthropogenic methane emissions, of which a major proportion is derived from livestock, coal mining, and rice cultivation [8]. To mitigate potential climate change-induced risks, China has adopted a new development philosophy in the coming era and proposed to achieve a carbon emission peak by 2030 and carbon neutrality by 2060 [9].

To fulfill international obligations and mitigate climate risk, a series of related activities and policies have been launched before the "carbon peak and carbon neutrality" statement [6]. Some of these policies were implemented to constrain carbon emissions from various aspects. For example, the Five-Year Plans (FYPs) stipulated the increasing target of energy intensity from the 2000s [10] and the decreasing target of fossil fuels from the 2010s [11]. Policies focusing specifically on emission reductions have also been introduced, such as Nationally Appropriate Mitigation Actions (NAMAs) in 2009 [12] and China's Intended Nationally Determined Contributions (INDCs) in 2015 [13]. FYPs were also introduced, focusing on the development of terrestrial carbon sinks and the increase in atmospheric carbon absorption since the early 2000s [10]. The aforementioned policies and their outcomes provide crucial necessary a priori knowledge for the designation of carbon neutrality pathways, related laws, and regulations [14].

Current CO_2 emissions are mainly attributed to the combustion of fossil fuels (Figure 1a). Coal accounts for a major proportion of China's CO_2 emissions among typical fossil fuels (~75%) and plays an important role in industrialization and urbanization [15]. The power generation and manufacturing sectors contribute to 44% and 38% of total CO_2 emissions, respectively [6]. Policies towards emission reduction goals were implemented to reasonably focus on these sectors. China primarily introduced top-down administrative measures, i.e., allocating the total reduction goals to local sectors. For example, during the 12th FYP, thousands of inefficient power plants and factories were closed by central and local governments [16]. The share of thermal power and factories with greater productivity increased significantly during this period for better management efficiency. In this top-down model, carbon emission allowances are assigned to each region, which are then reassigned by local governments. There are differences in the economy and carbon emissions in different regions, leading to different allocation standards for carbon emission allowances and different carbon abatement performances.

As a parallel tool for optimizing the power sector, the Carbon Emissions Trading Scheme (CETS) can also promote and manage the reduction of CO_2 emissions using a market-oriented mechanism [17]. The designation of China's CETS system referred to the European Union Emissions Trading Scheme (EU-ETS), including the same main features [18]. The carbon-trading market has been implemented in seven pilot markets since 2013 [19,20]. There are differences within the scheme in different regions, such as the quota magnitude and focusing sectors, leading to different emission-reducing performances [21]. The trading quota in pilot regions is still very small (<1% of nationwide emissions), outlining great potential once widely applied [6,22]. Recently, China's Ministry of Ecology and Environment expanded the CETS to other regions nationwide [23]. Carbon abatement performance in pilot areas with different economic bases and industrial structures thus provides the necessary experience for optimizing the scheme.

Simultaneously, the implementation of non-fossil energy, such as wind energy and solar energy, was encouraged. The 13th FYP aimed to increase the proportion of non-fossil energy supply to 15% nationwide [24]. This share will increase to 20% during the 14th FYP [25] and continue to increase after 2025. Under this background, the installation of wind turbines and photovoltaics has continued to increase.

Removing atmospheric CO_2 from natural ecosystems is necessary for achieving carbon neutrality goals [26]. Plants absorb atmospheric CO_2 via stomata and convert it into organic compounds through photosynthesis [27]. The difference between carbon uptake and ecosystem respiration can represent an ecosystem-scale sink capacity [28]. This capacity, however, reduces to a pseudo-equilibrium with its local environment since ecosystem productivity, which reaches stabilization in several decades [29,30], will be balanced by turnover and litter inputs from biomass turnover by heterotrophic respiration [31]. A harvesting removal of biomass (performing as a shift of forest age toward younger) is thus expected to keep the carbon sink capacity but not for low-efficiency usage such as bioenergy [32]. Although accurately quantifying its exact contribution is still challenging [33,34], forests account for the majority of China's terrestrial carbon sink (~80%, see Figure 1c) since trees assimilate and stock carbon in the live biomass during the growing stage [29]. However, China's forests acted as a carbon source from 1949 to the 1980s due to deforestation [35] but have shifted to being a carbon sink since the 1980s [36,37]. Several afforestation and reforestation campaigns contributed to this success [38,39]. Policies were also implemented to guide the recovery of China's forests; for example, the forest coverage goal increased from 18.2% in the 10th FYP to 23.04% in the 13th FYP [24].

To date, no study has conducted a comprehensive assessment of China's carbon emissions and progress in its efforts to reduce them, which would serve as a foundation for future decarbonization initiatives. In this study, we have gathered data from multiple sources to present a comprehensive evaluation of China's policies on major sectors in relation to carbon abatement and carbon neutrality, rather than focusing on specific areas. We have analyzed the reduction in fossil fuels, the increase in non-fossil energy, and the restoration of forests. Furthermore, we have discussed the strengths and implications of the relevant policies, which will aid in the development and optimization of laws and regulations in the subsequent stages.

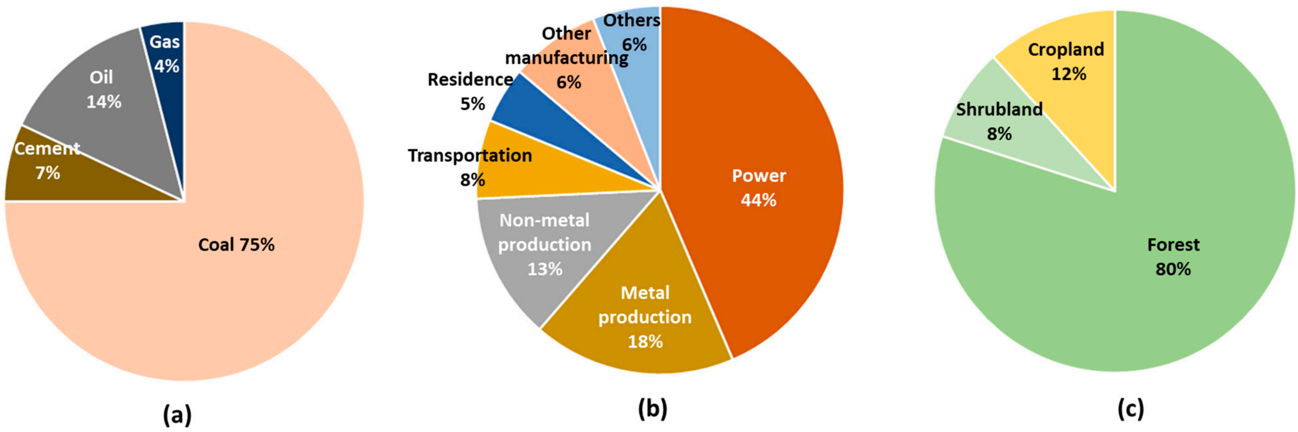

Figure 1. China's (**a**) consumption of fossil fuels, (**b**) CO_2 emission structure, and (**c**) terrestrial carbon sink structure. Data in (**a**, **b**) come from existing studies [6,40], from sources to sectors in 2017. Data in (**c**) come from reference [38]. The negative contribution of grassland (approximately −1%) has been removed since China's grassland has acted as a weak carbon source in recent decades [41].

2. Method

2.1. Data

We use statistical data from the National Bureau of Statistics of China to detect the trend of carbon emissions and remote sensing products to detect the trend of specific land cover categories. The calculation of carbon emissions considers the consumption of all fossil fuels. These statistical data from 2002 to 2019 are available at the National Bureau of Statistics of China: https://data.stats.gov.cn/english/ (accessed on 18 February 2023). The total CO_2 emissions (C) for the n kinds of fossil fuels can be written as:

$$\boldsymbol{C = 3.67 \times \sum_{i=0}^{n} E_i \times NVC_i \times CC_i} \quad (1)$$

where 3.67 is the multiplier to convert carbon consumption (t) into CO_2 emissions (t), E_i represents the annual consumption of the ith fuel (t) from statistical data, NVC_i represents the net calorific value of the ith fuel (TJ/t), and CC_i represents the carbon content per unit of energy of the ith fuel (t/TJ). Default values for NVC and CC can be found in Table 1. It should be noted that the combustion efficiency for each fuel was set to 100% for simplification.

Table 1. Default values during the calculation of carbon emissions. The values in this table refer to [42].

Fuel	NVC (TJ/t)	CC (t/TJ)
Diesel oil	0.043	74.1
Coke	0.028	107
Coal	0.021	101
Kerosene	0.043	71.9
Gasoline	0.043	74.1
Fuel oil	0.042	77.4
Gas	0.039	56.1
Crude	0.042	73.3

We collect data from the economic, industry, and technology sectors and carbon trading quotas to detect the driving factors of reducing carbon emissions in the pilot areas of the CETS since 2013. These data are also available at the National Bureau of Statistics of China. We focused on six pilot areas in this study: Beijing, Shanghai, Tianjin, Chongqing, Guangdong, and Hubei since the data from Shenzhen city can be combined into Guangdong province.

We combine remote sensing (RS)-based terrain observations and zonal statistical data to detect forest trends in China. The fraction of absorbed photosynthesis active radiation (FAPAR) is a common RS-observed index that can describe terrestrial greenness and leaf density. There are studies focusing on the terrestrial vegetation trend by employing FAPAR [43,44]. Here, we collect FAPAR from the MCD15A3 product with a 4-day interval and 500 m spatial resolution from 2003 to 2020. The quality control band was used to mask the low-quality grids within the original images. We calculate the monthly average value and the yearly average value. The variation trend of each forest grid is then calculated. In this step, we use the annual MCD12Q1 product to mask non-forest grids.

2.2. Related Policies

Policies for reducing CO_2 emissions and increasing carbon sinks are evaluated by the aforementioned data in this study. The FYPs in China are the overall development guidelines for the work of governments at all levels and sectors. Major projects, measures, and policies from local governments should be introduced in accordance with the goals of the FYPs. The nation-scale goals of the FYPs regarding carbon emissions, non-fossil energy installation, and forest recovery were allocated from central to local governments and executed as the basis for the governments to perform their duties (Figure 2). To reduce carbon emissions by improving efficiency, the carbon intensity was planned to reduce by 20% in the 11th FYP to 18% in the 14th FYP and was planned to reduce 2005 carbon intensity levels by 40–45% and over 65% by 2020 and 2030 in NAMA and NDCs, respectively [6]. The carbon-trading mechanism has also been introduced in CETS pilot regions since 2013. These pilot regions have promulgated some local regulations and policies to regulate the carbon emissions trading mechanism, covering different sectors and having different quotas.

In addition to limiting carbon intensity and CO_2 emissions, the share of non-fossil fuels in primary energy consumption was also planned to increase from 11.4% in the 12th FYP to 20% in the 14th FYP. The forest coverage increased from 18.2% in the 12th FYP to 23.04% in the 13th FYP.

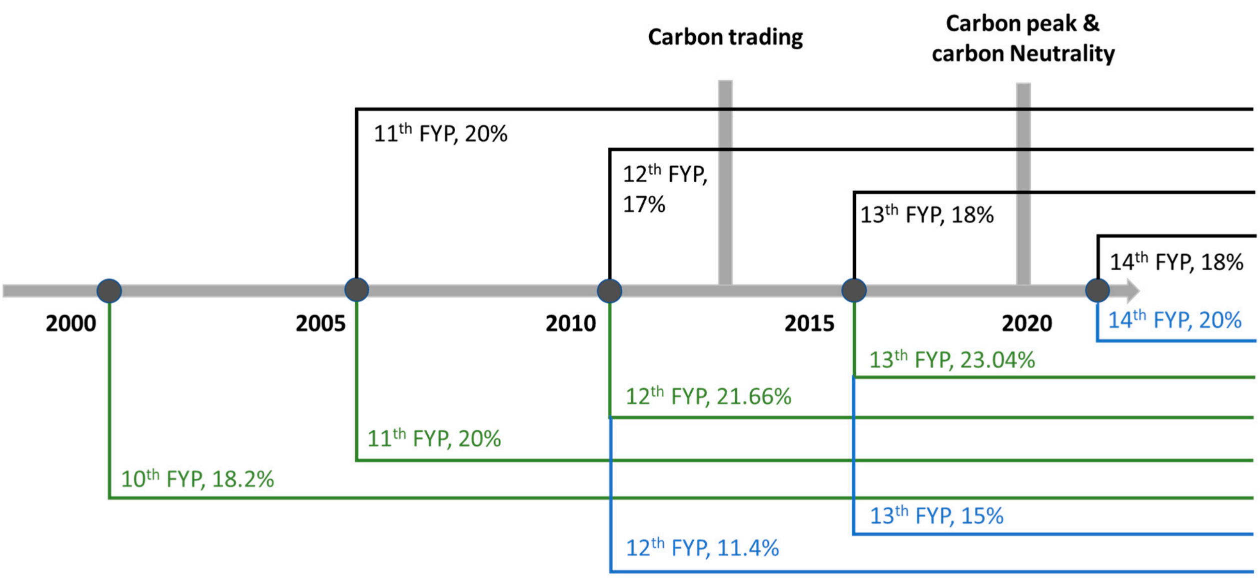

Figure 2. Timeline of China's major policies related to carbon neutrality since 2000. The policies and percentages in black represent the carbon intensity reduction goal compared with the start of this period. The percentage in green represents the increasing goal of forest coverage, and the percentage in blue represents the increasing goal of non-fossil fuels.

3. Results

3.1. CO_2 Emissions

China's CO_2 emission trend can be divided into two stages: before 2012 (CO_2 emissions increased 729 Mt per year, p value < 0.001) and after 2012 (CO_2 emissions increased 230 Mt per year, p value < 0.001). This significant transfer happened at the start of the 12th FYP. With the guidance of the 10th and 11th FYP, nearly half of the provinces have reduced their carbon intensity since ~2010 by improving energy efficiency and deploying and transforming low-carbon technologies [6] =. The reduction of consumed coal contributed to this transfer (a median of nearly 1% of annual reduction), indicating that China's power structure is optimizing towards a cleaner scheme (Figure 3). The consumption of gasoline and kerosene has increased significantly due to the development of China's economy and transportation [45].

Compared with other provinces, pilot regions with CETS had a more moderate increasing trend of CO_2 emissions than those nonpilot regions in stage I (7.7 $\pm$ 3.8% year^{-1} and 8.7 $\pm$ 4.9% year^{-1}, respectively) and achieved a negative emission trend in Stage II ($-$1.3 $\pm$ 4.1% year^{-1}, see Figure 4b, c), meaning that some of the regions have achieved negative emissions in recent years. Four of six regions achieved negative CO_2 emissions. Among these six regions, the greatest difference between the two stages, i.e., the reduction rate of CO_2 emissions, occurred in Chongqing city (7.8% year^{-1} compared with $-$2.8% year^{-1}), although it has the highest ratio of the second industry and lowest urbanization rate (Table 2). The carbon-trading quota covered ~60% of total emissions and six major sectors (metal, power, chemistry, etc.), which partly contributes to this success. Beijing has the greatest decrease in emissions after the implementation of the CETS ($-$6.0% year^{-1}). This is also reasonable since Beijing has the lowest proportion of secondary industry. Since Guangdong and Hubei provinces have lower quotas and greater scales of industry than the other four pilot cities, the reduction rates of CO_2 emissions were not as satisfying as those in other regions.

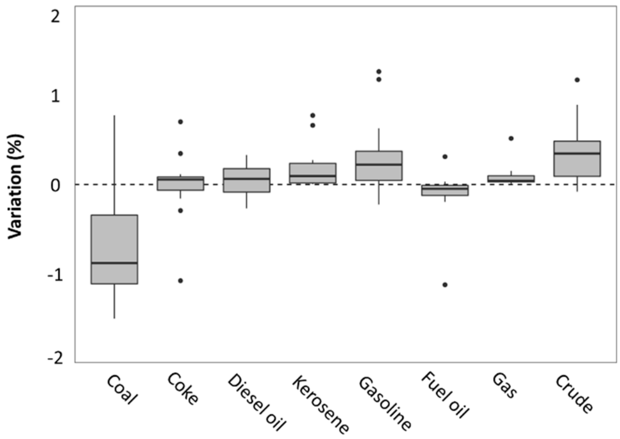

Figure 3. Variation trend (percentage year^{-1}) of the main types of fossil fuels in all provinces.

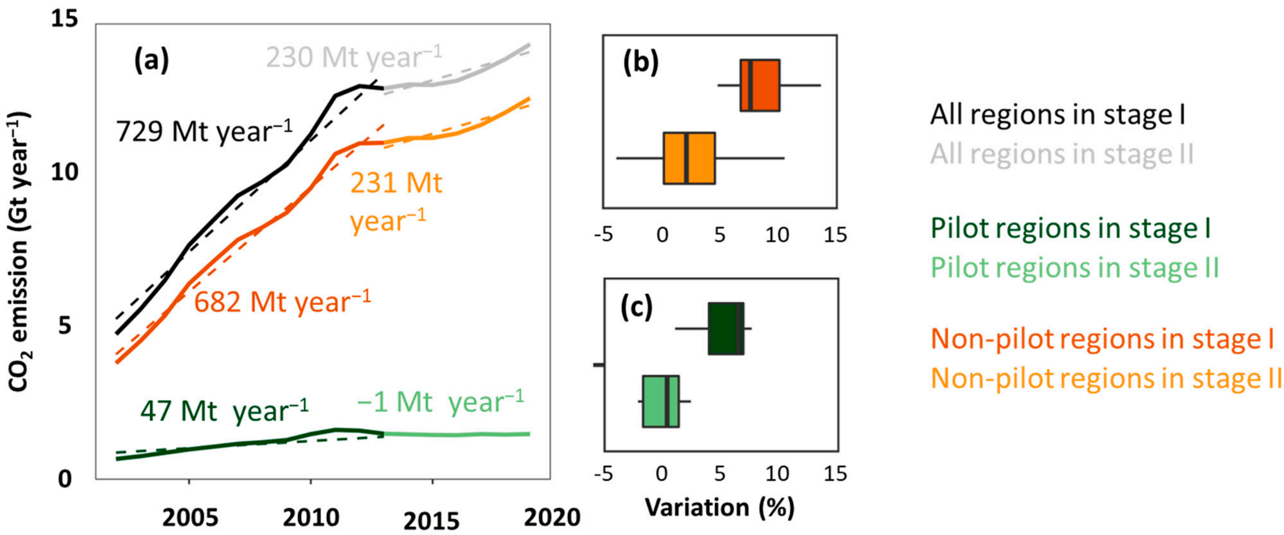

Figure 4. Temporal trend of CO_2 emissions in all regions, pilot regions with CETSs, and nonpilot regions. The dashed line in (**a**) represents the fitted trend. Two colors within the same curve represent two stages (stage I and II). (**b**,**c**) represent the distribution of the carbon emission variation rate (%) for pilot and nonpilot regions, respectively.

Table 2. Comparison of CO_2 emission reduction performance in two stages and related factors in pilot regions. Industry proportion is calculated by the ratio of gross domestic product (GDP) from the second industry to total GDP. The urbanization rate is calculated by the ratio of urban residents to total residents.

Region	Reduction Rate in Stage I (%)	Reduction Rate in Stage II (%)	Quota (%)	Company Numbers	Industry Proportion (%)	Urbanization Rate (%)
Beijing	0.7	−6.0	40	415	19.3	86.5
Tianjin	7.1	−2.3	55	114	43.4	83.3
Shanghai	3.1	−0.1	57	191	34.2	89.3
Chongqing	7.8	−2.8	60	242	46.3	59.7
Guangdong	7.0	2.1	54	200	46.8	69.5
Hubei	6.1	1.0	35	138	46.1	57.2

3.2. Clean Energy

There was a significant increase in wind turbine and photovoltaic equipment reported by statistical data, especially after the start of the 12th FYP, in which the share of non-fossil energy was being encouraged by published policies for the first time (21.9 million

KW year^{-1} for wind power and 32.5 million KW year^{-1} for solar power, p value < 0.01, see Figure 5a). We find an even higher increasing rate after 2017 for both energy equipment (~40 million KW year^{-1}). These newly installed non-fossil power generators replace fossil fuels and thus reduce CO_2 emissions. According to the China Energy Statistical Yearbook [46], in 2020, wind and photovoltaic powering equipment produced 4.7 and 2.6×10^{11} KW h, respectively, which saved 126 Mt of coal and reduced corresponding CO_2 into the atmosphere.

The distribution of installed power capacity reported by statistical data is consistent with the result detected by deep learning [47,48]. Spatially, wind turbines are mainly distributed in northern China, especially Inner Mongolia since there is a more considerable wind resource and less loss of energy during transmission (Figure 5b). Photovoltaics are mainly distributed in eastern China, such as Shandong and Hebei, which are demanded by local factories and residences (Figure 5c).

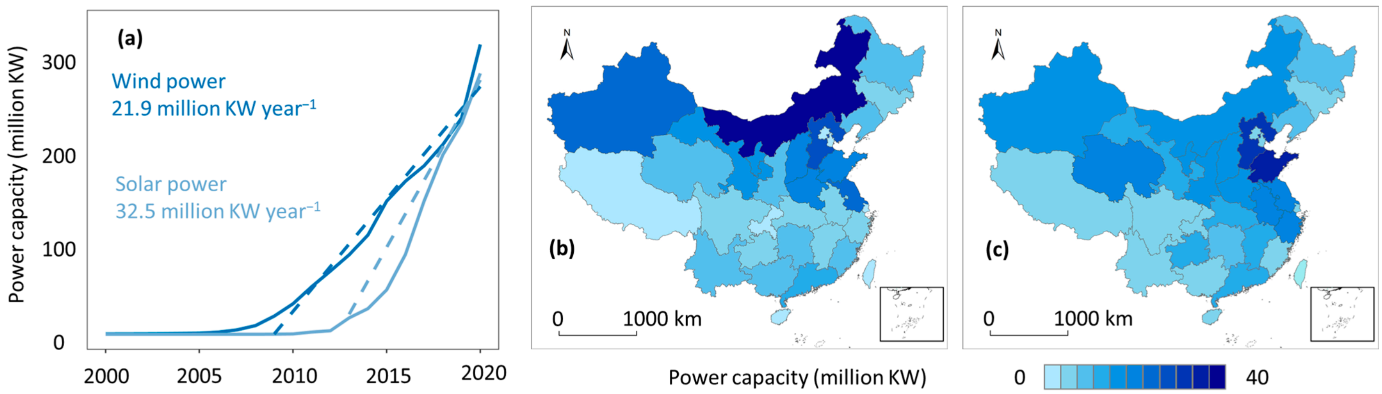

Figure 5. Temporal (**a**) and spatial trends (**b**,**c**) of China's wind and solar power capacity. Data in (**b**,**c**) come from 2021.

3.3. Forest Recovery

In agreement with the results of existing studies [43,49], there was an overall greening trend in China's forest areas from 2003 to 2020 detected by an RS-based greenness observation (Figure 6), indicating a success of forest recovery during this period [41].

Since RS-based FAPAR observations with medium spatial resolution can be considered a metric of leaf density in each pixel, this greening trend is mainly contributed by the increase in forest area (i.e., forest fraction within each mixing grid) and leaf density. The area of forest reported by the forest inventory increased significantly (4260 Kha year^{-1}, p value < 0.001, see Figure 6b). Several RS-based land cover products support this increase [50]. This increase in forest area was mainly contributed by the expansion of natural forest (2530 Kha year^{-1}, p value < 0.001) and partly contributed by artificial forest (1730 Kha year^{-1}, p value < 0.001). In addition, in some mature forests, greening is the result of increasing leaf density, which benefits from the CO_2 fertilization effect [51] and increased local water supplementation [52]. An increasing trend of aboveground biomass in China's boreal/temperate forests detected by microwave RS imagery also supports this phenomenon [53].

The increased natural forest is mainly distributed in western China, such as Xinjiang, Xizang Sichuan, and Yunnan (Figure 7). Since the available water limits plant growth in most parts of China [53], the increasing trend of precipitation in these regions mainly contributes to the expansion of natural forests. The increased artificial forest is mainly distributed in Inner Mongolia. This was a result of the Three-North Shelter project, which was designed to mitigate desertification and air pollution [54].

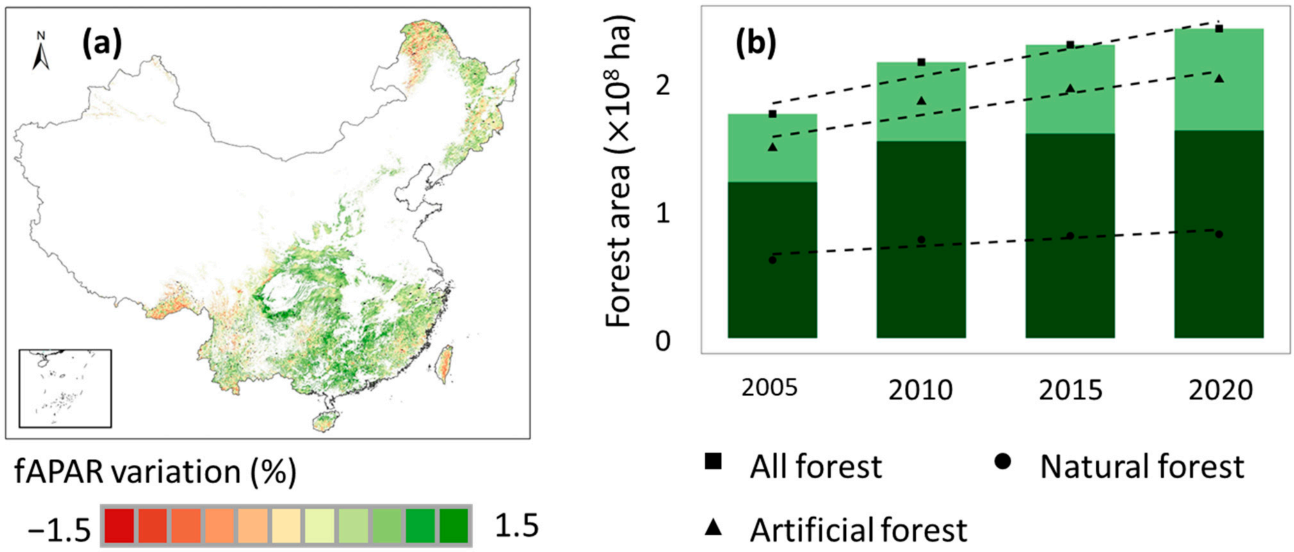

Figure 6. Temporal trend of China's forest (**a**) greenness and (**b**) area. The non-forest in (**a**) is masked by the MODIS land cover product. The trends of all forests, natural forests, and artificial forests are displayed by different colors and labels.

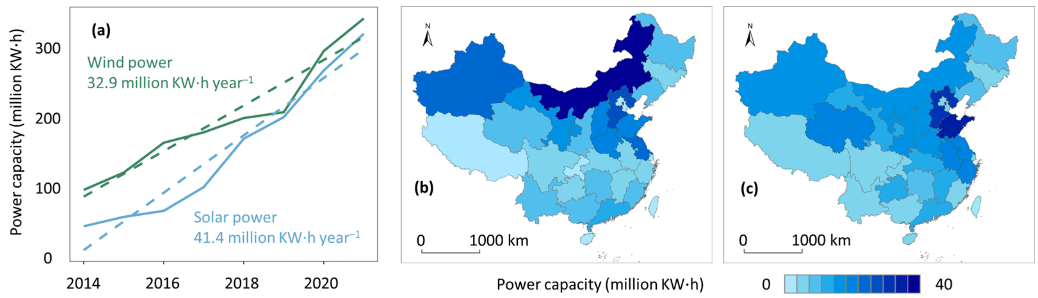

Figure 7. Trend distribution of China's (**a**) natural and (**b**,**c**) artificial forests (Kha year^{-1}).

4. Discussion and Implication

4.1. CO_2 Abatement

China's increasing trend of CO_2 emissions has shifted to be more moderate since the 2010s. This shifting was partly driven by the separated reduction goals of carbon intensity in the 12th and following FYPs, indicating a greater economic efficiency from the same carbon emissions. This success relies to a large extent on a nation-level blueprint and regional-level emission reduction practices. For example, to reduce carbon intensity by 18%, as proposed in the 13th FYP, various regional targets at different administrative levels were set. Accordingly, different government levels might formulate specific implementation plans, as well as their own targets for reducing energy intensity and increasing energy efficiency [6]). There are differences in the outcome performance. A sufficient economic and technological basis would accelerate the reduction of carbon intensity. Most of the regions can achieve and even exceed the given target, such as Beijing (2.5% exceeding) and Tianjin (1.5% exceeding). In contrast, some of the developing regions or regions with a considerable proportion of power generating industry cannot achieve the designed target, such as Inner Mongolia (3% failing) and Ningxia (performing a nonsignificant decreasing trend). China will keep its carbon abatement trend towards the carbon peak and carbon neutrality target, which would be maintained by this top-down designation strategy. The challenge of achieving the nationwide target in regions with unsatisfactory abatement performance requires coordinating bottom-up efforts from related sectors. Additionally, the designation of regional goals should be optimized with a more comprehensive understanding of local conditions. A stricter target in regions with a considerable economic and technological basis would enhance the overall performance, while a looser target in power-intensity regions would be more reasonable.

Although CETS in the pilot regions achieved a satisfying performance in accelerating carbon abatement, the nationwide trading scheme covering major emission sectors has not been launched for a long time (https://www.iea.org/reports/chinas-emissions-trading scheme, accessed on 18 February 2023). The current nationwide regime is only for the electricity sector and is planning to be expanded. However, there are differences between the economic basis and industry structure within different provinces, which contributes to carbon abatement in this study. For example, the carbon price significantly affects the performance of carbon abatement, which relates to the local industry structure. The carbon emission quota should consider the natural carbon abatement caused by technology development [21]. Similar to setting the carbon reduction target in the FYPs, the designation of the nationwide scheme should thus consider the regional economic and technological basis [55].

As shown in Section 3.2, there was a significant increase in non-fossil capacity from the 2010s, which is an ideal substitution for traditional fire-based energy. This increase met the goal of the 12th and 13th FYP, allowing the target of 15% in the 14th FYP to be met. More non-fossil energy is required to achieve the goal of carbon neutrality before 2060 [56]: ~1200 million KW and 3700–5400 million KW of solar and wind capacity is required by 2030 and 2050, respectively, to fulfill the Paris Agreement [57,58]. We can confidently predict that there will be considerable potential to keep, and even enhance, this increasing trend in the near future. The development of energy infrastructure, such as storage and transmissions, is thus urgently needed. For example, as we can see from Figure 5, the solar energy capacity in the Tibetan Plateau is far from capable enough to fully utilize its radiation resource. Increasing the storage and transmission capacity substantially helps to relieve the geographical constraint and to utilize the energy in these regions [59–61].

4.2. Terrestrial Carbon Sink Dynamics

In recent decades, the majority of China's terrestrial carbon sink has been contributed by the recovery of forests, which was shown in Chapter 3.3. In the 1980s and 1990s, China's annual net natural carbon sink accounted for approximately 30% of its anthropogenic CO_2 emissions. According to a recent study by reference [33], this trend has continued to increase. This increase can be attributed to the nationwide goal of increasing forest area through various afforestation projects. Some examples of successful regional afforestation activities include the "Grain for Green project, " which began in 1999 and involves converting croplands on steep slopes into forests or grasslands to reduce soil erosion, and the "Shelterbelt Project, " which was launched in the 1970s to combat desertification by planting shelterbelts of trees to reduce the spread of sand and dust [62]. The expanding trend in the area of newly planted artificial forests in North China, depicted in Figure 7, suggests that these initiatives have been successful.

The regrowth of forests, i.e., reforestation, especially temperate forests, significantly enhances the carbon sink, indicating the importance of forest harvesting [31]. However, attention should also be paid to the lifespan of forest products, since wood usage determines the storage period of carbon [63]. For example, paper and fuel wood usually have shorter lifespans (one to several years) than sawn timber and other bio-based materials (decades), which can store carbon in buildings. Introducing waste wood and paper recycling practices can thus increase the share of wood usage with long-term carbon storage [64]. Simultaneously, substituting mineral-based engineering materials with wood- or bio-based materials increases the carbon sink in buildings [65], which is a safer way to store carbon than pumping CO_2 underground [66].

Nevertheless, there is a ceiling of increasing carbon sink through afforestation and reforestation. Plant growth is also influenced by the feedback from hydrological processes [67], such as the limited vegetation greenness by local water availability [52] and environmental aridity [67]. One issue is that large-scale afforestation may worsen local drought conditions by reducing runoff and soil moisture, exacerbating water conflicts in arid and semi-arid regions [68,69]. Therefore, it is necessary to conduct a systematic evaluation of water resources before undertaking large-scale afforestation. Failure to do so can result in wasted resources and tree mortality [70]. Additionally, for some mature forests, the potential for increasing carbon sink may be limited. To design and optimize a carbon abatement path, it is crucial to accurately predict the potential for increasing carbon sink through afforestation and reforestation [71].

In addition to vegetation ecosystems, wetlands are another important landscape that contributes to the carbon cycle, which can benefit carbon sinks by storing dead organisms in the sediment [72] but can also accelerate warming by emitting methane into the atmosphere [73,74]. China suffered a loss of coastal wetlands: ~50% of coastal wetlands were replaced by other landscapes before 2000 [75]. Based on RS-based time-series monitoring using ~62, 000 images, there was a decreasing trend in China's coastal wetland area before 2012 [76]. A modest improvement was noticed following the implementation of ecological civilization construction [77], which is an initiative aiming to construct a society that is sustainable and environmentally friendly, while also maintaining a balance between economic progress and ecological preservation, and strives to establish a relationship between humans and nature that is harmonious and collaborative [76,78]. Another wet landscape, vegetated wetlands, has been subject to silent losses in recent decades. Hydroperiods and other ecosystem characteristics enable certain plant species to grow, resulting in a range of wetland ecosystems seasonally covered by vegetation, ranging from sparse vegetation to dense woody plants. With the variance in canopy conditions, vegetated wetlands can be extremely difficult to map and monitor compared to other permanent or open-surface water wetlands.

4.3. Carbon Peak and Neutrality Laws and Policies

Laws and policies are the basic weapons to enable the achievement of carbon targets. With the goal of achieving a "carbon peak and carbon neutrality", China has formulated corresponding laws and policies. While these policies and laws have had some positive effects on reducing CO_2 emissions and increasing carbon sinks, they still have some shortcomings. Continuing to improve these policies and laws will further enable the Chinese government to meet its "carbon peak" and "carbon neutrality" targets.

4.3.1. Refinement of the National Carbon Emissions Trading Mechanism

The carbon emissions trading mechanism is one of the important mechanisms for the Chinese government to control carbon emissions [79]. The core of the carbon emissions trading mechanism is the circulation of carbon emission allowances. Carbon allowances are a tradable commodity, whereby participants with large emissions can purchase allowances from participants with small emissions [79]. Emissions trading mechanisms promote emission reductions through economic incentives. Nationwide carbon allowance trading started in 2021. Combined with the carbon emissions trading policies and effects of the seven pilot regions, the establishment of a national carbon emissions trading mechanism should focus on the following aspects:

1. China should expedite carbon emissions trading legislation and establish a dedicated regulatory authority. Several government departments in China have formulated carbon emissions trading policies and can supervise carbon emissions trading by analyzing the experience of pilot areas and the policies and regulations that have been formulated in China. This can lead to confusion in the regulation of carbon emissions trading. The carbon emissions trading mechanism in some pilot areas is operating well and can play a positive role in reducing carbon emissions. However, there are still some areas where carbon emissions have not been reduced. Therefore, it is necessary to promulgate a unified legal system [80], including laws, administrative regulations, and policies. Under a unified carbon emissions trading legal system,

a dedicated carbon emissions regulatory authority can promote the same emission reduction effect in each region;
2. The carbon emissions trading mechanism should set flexible and strict carbon emission allowances. Strict carbon emission allowances will bring greater cost and pressure to enterprises, while loose carbon emission allowances will reduce the enthusiasm of enterprises to reduce emissions [81]. Therefore, the setting of carbon emission allowances will affect the emission reduction effect of the carbon emissions trading mechanism. The formulation of carbon emission allowances should consider the social cost of carbon [82]. When the social cost of carbon is the same as the marginal abatement cost [83], the carbon emissions trading mechanism is more efficient. From the experience of Beijing and Shanghai, the carbon emission allowances in these two regions are not fixed but constantly change according to the market. The carbon reduction effect of these two regions is also better than that of other pilot regions. Therefore, the carbon allowances in national carbon emissions trading should be set flexibly and strictly according to the social cost of carbon and market changes;
3. China's carbon emissions trading mechanism should clarify the legal responsibilities and penalties of participants. During the pilot process of carbon emissions trading, some regions did not complete the emission reduction targets, and some companies did not strictly abide by the trading rules. However, they have not suffered any serious adverse consequences. This is because carbon emissions trading policies and regulations do not clearly define the responsibilities and penalties for breaking the rules. Therefore, local governments and enterprises have no incentive to actively participate in carbon emissions trading. Therefore, it is necessary to stipulate the legal responsibilities and punishment measures of all parties, including the government and enterprises, in the formulation of a nationally unified carbon emissions trading law.

4.3.2. Stringent Emission Regulation Legislation and Policies

China's current regulation of CO_2 emissions is not strict. This is reflected in two aspects. First, the Chinese government has not defined CO_2 as a harmful greenhouse gas. Different legal texts or official documents may list CO_2 as a greenhouse gas, but it is not a legally harmful gas. This has brought difficulties to the regulation of greenhouse gas emissions. One possible outcome is that the regulation of CO_2 emissions depends on the regulators' understanding of China's legal texts or policies. This led to the imbalance of greenhouse gas regulation. Another result is that when CO_2 emissions do not cause the deterioration of air quality, regulators will not pay attention to CO_2 emissions. Therefore, China should stipulate in the law that CO_2 is a gas harmful to the environment. Second, it is difficult to obtain accurate CO_2 emission data. Without accurate CO_2 emission data, relevant enterprises and institutions cannot be supervised. China's Environmental Protection Law requires the monitoring of pollutant emissions by key pollutant-discharging enterprises. However, monitoring cannot cover all CO_2 emission enterprises or institutions. Therefore, China's Environmental Protection Law should be amended to expand the scope of monitoring enterprises and institutions. The monitored objects shall include all enterprises and institutions that emit CO_2.

4.3.3. Laws and Policies towards Increasing Carbon Sink

The Chinese government should pay attention not only to the growth of forest quantity but also to the quality of forests when formulating forest laws and policies. Forests have a strong carbon storage function and are an important area of carbon sinks. The quantity and quality of forests influence the process of carbon neutralization. China has enacted a large number of laws and policies for afforestation. Afforestation is a basic national policy of China [84]. However, current laws and policies are more concerned with forest areas. For example, the 13th Five-Year Plan has set a target for forest coverage. In 2020, the forest coverage rate reached 23.04%, and the forest volume reached 16.5 billion cubic meters [24].

However, the blind pursuit of forest quantity may bring about other ecological issues, such as the local drought caused by forest evapotranspiration. To increase the capacity of forest carbon sinks and enhance their ecological function in a more sustainable way, the Chinese government should also pay attention to the quality of afforestation when formulating forest laws and policies. The forestry administrative department should strengthen the monitoring of forest quality and related indicators to improve the capacity of forest carbon sinks.

In addition to forests, other ecological elements also have a certain carbon sink capacity, such as wetlands and grasslands. The Chinese government should formulate unified carbon sink laws and policies. Although the Chinese government formulated the Wetland Protection Law in 2022 for the protection of both coastal and noncoastal wetlands, an inventory related to systematic wetland categories is still lacking.

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