THEMATIC ISSUE

The sustainability assessment of CO_2 capture, utilization and storage (CCUS) and the conversion of cropland to forestland program (CCFP) in the Water–Energy–Food (WEF) framework towards China's carbon neutrality by 2060

Yachen Xie[1,2] · Zhengmeng Hou[3,4] · Hejuan Liu[5] · Cheng Cao[6] · Jiaguo Qi[1,2]

Abstract

The global warming induced by the emission of greenhouse gases, especially the carbon dioxide, has become the global climate and environmental issues. China has been working in the CO_2 emission reduction and carbon sinks with the purpose of becoming the carbon-neutral country by 2060. The CO_2 capture, utilization and storage (CCUS) technologies and the reforestation technology represented by the Conversion of Cropland to Forestland Program (CCFP) have great potential for sinking CO_2 emission. However, the trade-off among CCFP, CCS/CCUS and Water-Energy-Food (WEF) nexus are not well evaluated. In this paper, the remote-sensing data are collected and used to evaluate the sustainability of CCFP by analyzing the variation of land use and land cover (LULC), crop production, etc. The results show that 13.29% of the cropland in 2001 vanished and converted to grassland (8.3%), mosaic cropland (3%) and urban land (0.98%) in 2019, demonstrating that the CCFP is successful in both WEF nexus and carbon sink. The total crop production has increased around 50% between 2001 and 2019, implying that the CCFP will not lead to the food risk during the conversion of croplands into other types of land in China. A sustainable implementation of CCFP and other environmental Payments for Ecosystem Services (PES) policies in 2019–2060 could reach an estimated total growth of 7.462 billion m^3 in comparison of that in 2018 and the total plantation forest stock of about 10.852 billion m^3 in 2060, with a corresponding minimum CO_2 sink of 2.90 billion tons in 2060. The estimated peak of net equivalent CO_2 emissions before 2030 is about 11.0 billion tons and could not be reduced to zero by 2060 without the large-scale application of the CCS/CCUS technologies as geological sequestration of CO_2. Besides, the application of CCS/CCUS can be beneficial for WEF, e.g., through replacing the water by CO_2 during energy production, especially in the shale gas production in the regions with high water risks in China. In one word, CCS/CCUS and CCFP are two decided pathways of carbon sequestration and should be systematically applied to achieve China's carbon neutrality by 2060.

Keywords CCUS · CCFP · WEF nexus · Carbon sequestration · Carbon neutrality

✉ Zhengmeng Hou
hou@tu-clausthal.de

✉ Jiaguo Qi
qi@msu.edu

Extended author information available on the last page of the article

Introduction

Climate change and global warming lead to serious consequences, such as sea level rise, glacier melting, storms, floods, droughts, etc., threatening humans' survival and well-being, thus attracting both the scientific community and the public's attention. One of the critical reasons leading to global warming is greenhouse gas emissions, especially the atmosphere's carbon dioxide. More and more global governments have taken action to reduce carbon dioxide emissions of limiting global temperature growth to 1.5 °C within this

century compared with the pre-industrial level (Edenhofer et al. 2014; Rogelj et al. 2016).

Since carbon dioxide emission depends on the amount of carbon escaped from the carbon cycle, there are mainly two ways to reduce the atmospheric carbon dioxide: (1) reduce carbon emission into the atmosphere and (2) enhance the carbon sequestration. Except for reducing carbon dioxide emission toward energy production, transportation, etc., improving carbon sequestration is also crucial to accomplish the carbon–neutral goal. Two types of efforts can be made to enhance the carbon sequestration: (1) improve the natural carbon sink by soil, vegetation, and ocean; (2) enhance the capture/sequestration amount of CO_2 that are emitted during energy production process.

In terms of efforts to mitigate global warming, China is obviously crucial, and any successful international effort to stabilize greenhouse gas emissions will inevitably include China (Barbi et al. 2016). As China overtakes the US and becomes the world's largest carbon emitter, the Chinese government faces tremendous challenges to reduce carbon dioxide emissions. China first targeted at reducing the carbon intensity by 18% in 2016–2020 (The 13th Five Year Plan 2016). Furthermore, China's president Mr. Xi has made a statement in UN 2020 that China pledges to be carbon neutral by 2060 and aims to hit peak carbon emissions before 2030 (McGrath 2020). Through the afforestation process, Chinese land biosphere sink is equivalent to about 45% of annual anthropogenic carbon emission (Wang et al. 2020), but it is still a long way to go to totally reduce the carbon emissions from energy production. Therefore, China has made great efforts to reduce the CO_2 concentration in the atmosphere through both enhancing terrestrial carbon sink and improve the underground carbon storage by carbon capture, sequestration (CCS) and utilization (CCUS) technologies during the energy production process.

To mitigate the hazard of vast land degradation, China has been implementing various environmental Payments for Ecosystem Services (PES) policies after the Yangtze River flooding in 1998, including the Natural Forest Protection Program (NFPP), the Conversion of Cropland to Forestland Program (CCFP) that is also called Grain for Green (GFG), etc. These policies have been launched to increase natural carbon sink by protesting natural forests and converting some croplands into forests or grasslands, which takes up 56% of the total carbon sink in China during the first decade of the twenty-first century (Lu et al. 2018).

The CCFP is an extensive public PES program by compensating farmers to convert the ecologically vulnerable croplands or croplands with high slopes to forests or grasslands (Gauvin 2010). The CCFP can reduce soil erosion, sediment transport and flood frequency (Li et al. 2019); thus the carbon sequestration has been strengthened both by vegetation and soil through increasing soil organic carbon

(SOC), particulate organic carbon (POC) and light fraction organic carbon (LFOC) (Shi et al. 2020). However, various concerns and debates still exist towards the utilization of CCFP for the sustainability and the food security issue linked to the reduction in cropland area caused by the conversion into forests (Xu et al. 2006; Rodríguez et al. 2016).

Another important carbon emission reduction method is the CCS/CCUS technology, which has been widely used in reducing the CO_2 emission released from large stationary point sources during the energy production process such as thermal power plants, synthetic ammonia industry, iron and steel plants, cement plants, etc. (Liu 2015). Globally, the CO_2 usually be injected at deep depth more than 800 m and stored in different geological sites, such as deep saline aquifers, depleted oil and gas reservoirs, deep unmineable coal seams etc. The CCUS technology is much competitive due to the offset of cost by enhancing the recovery of oil (CO_2-EOR), coalbed methane (CO_2-ECBM), natural gas (CO_2-EGR) or geothermal energy. Since the 1970s, the CO_2 has been used in the commercial-scale oil production in the USA (ACCA21 2012). Studies on CO_2-ECBM and CO_2-EGR started in the 1990s (Puri and Yee 1990; van der Burgt et al. 1992), but it is still at the very early test stage of CO_2-enhanced shale gas production (Pei et al. 2015). Besides, the CO_2 is used as the circulation fluid of the geothermal system to extract geothermal energy (Brown 2000). Till the end of 2016, there were 38 large-scale CCS and CCUS projects and about 70 pilot-scale engineering CCUS projects globally and the top three locations are North America, Asia and Europe. Most of these engineering are CO_2-EOR or pure CO_2 capture projects, followed by CO_2-ECBM and CO_2 sequestration in saline aquifers (Liu et al. 2017).

The CCFP and CCS/CCUS have tremendous success in carbon sinks/sequestration. However, the large PES policy may trigger the variation of land use and land cover (LULC), which can lead to unexpected consequences on local natural resources and cropland production. The CCS and CCUS technologies applied in the energy production process may require much water consumption and cause the security issue of water resources. Therefore, there have been strong debates on the potential food security risk driven by CCFP and water security risk caused by CCS/CCUS.

When evaluating the policy implementation and the government efforts, it is insufficient only to examine the success of the primary goal. The trade-off analysis of policy's impacts on other aspects is also crucial in policy assessment. In order to understand whether these two primary types of carbon sequestration efforts are sustainable, it is urgent to study their trade-offs. The CCFP is the largest and most critical PES policy in China. Still, the decrease in cropland cover area through conversion may reduce crop production and lead to food security issues. The associated LULC change

may have further impacts on water resources. The CCS and CCUS technologies applied in power plants can improve water consumption during the carbon capture process and affect energy production.

The trade-offs of CCFP, CCS/CCUS and WEF nexus are mainly between the carbon sequestration itself and food, energy, and water resources. The WEF nexus is a well-known framework that has been widely used in sustainable development because it can maximize the synergies and minimize trade-offs between these three sectors (Bazillian et al. 2011). Food, energy, and water are essential and closely linked to almost all aspects of human well-being (Pittock et al. 2015). Many researchers have applied the WEF nexus in carbon regulation issues. But most of them are theoretical (Daher et al. 2015; Huang et al. 2020; McCarl et al. 2017), but it is rarely focusing on carbon sequestration.

In this paper, the WEF nexus is applied in the sustainability assessment of CCFP and CCS/CCUS without considering other factors (e.g., geological risk by CCUS, policies and economic sustainability, etc.) by answering the following three questions: (1) How important are CCS/CCUS as geological CO_2-sequestration and CCFP as natural carbon sinks for China's carbon neutrality by 2060? (2) How does the implementation of CCFP affect cropland LULC, crop production, etc., in the WEF nexus? (3) How does the utilization of CCS/CCUS technologies affect water consumption during energy production in the WEF nexus?

Methodology

Conceptual framework of WEF nexus

Water, energy, and food securities are of crucial importance for global sustainability. Driven by global population growth, urban sprawl, climate change, and shifting consumption patterns, global demand for these three types of resources is increasing rapidly (Biggs et al. 2015). The Water, Energy and Food (WEF) security nexus–solutions for the green economy has been proposed in 2011, which provides the first platform for consideration water–energy–food into one nexus perspective. The WEF nexus framework is an interdisciplinary structure that can emphasize the WEF sectors separately and their inter connections. It can reflect the status of the fluctuating WEF nexus system, the trade-offs, and synergies caused by changes in different sectors. The WEF nexus framework can help better understand the sustainability considering not only one aspect but also the chain effect caused by the changes of that aspect. Many researchers and institutions have conducted many sustainability studies based on the WEF nexus (Leck et al. 2015; Albrecht et al. 2018).

Data acquisition and workflow for the sustainability of CCFP policy

Both the remote-sensing data and local statistical data are obtained for the sustainability analysis of CCFP. Remote sensing imagery includes LULC, precipitation, net primary production (NPP) and evapotranspiration (ET) between 2001 and 2019. Two sources of LULC data including the LULC product with the spatial resolution of 500 m (MCD12Q1) obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) and the LULC data extracted from the European Space Agency Climate Change Initiative (ESACCI) are used in this paper. The ESACCI yearly classification imagery of LULC has the 300-m spatial resolution. The yearly LULC classification data with the International Geosphere Biosphere Program (IGBP) schemes are extracted from MODIS. Precipitation data are from Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) with 0.05 is degree resolution. The pentad data are combined into yearly data. Yearly NPP data are obtained from MODIS Terra NPP product (MOD17A3HGF) with the 500-m spatial resolution and the evapotranspiration data are also from MODIS (MOD16A2) with the 500-m spatial resolution. The 8-day imagery is combined into yearly time series data. DEM data are obtained from the Shuttle Radar Topography Mission (SRTM). The water surface area classification is from the global yearly surface water classification history dataset, with 30 m spatial resolution, provided by the Joint Research Centre (JRC) of the European Commission (Pekel et al. 2016).

In situ statistical data are extracted from National Bureau of Statistics of China, including marine/freshwater aquatic production, agricultural diesel usage, fertilizer usage, rural hydropower plants, reservoir number and capacity, etc.

The general framework and overall analytical method for data processing related with CCFP are shown in Fig. 1. To detect the variation in the LULC map for detailed analysis, the land cover products from MODIS and ESACCI are re-classified. The LULC datasets of MODIS are classified according to the standard of IGBP (Friedl et al. 2002), which has 17 LULC classes and they are grouped into nine categories in this paper (see Table 1). The ESACCI land cover product has 28 LULC types, and they are grouped into 10 LULC types in this paper (see Table 2).

NPP can represent the general carbon sequestration capacity and the productivity of cropland. The total NPP and the NPP in cropland of China are calculated separately. The yearly total precipitation data in China are used to illustrate the change of water resource. Evapotranspiration data are combined with the cropland area to represent the water usage of irrigated agriculture. The difference between precipitation and evapotranspiration can represent the water
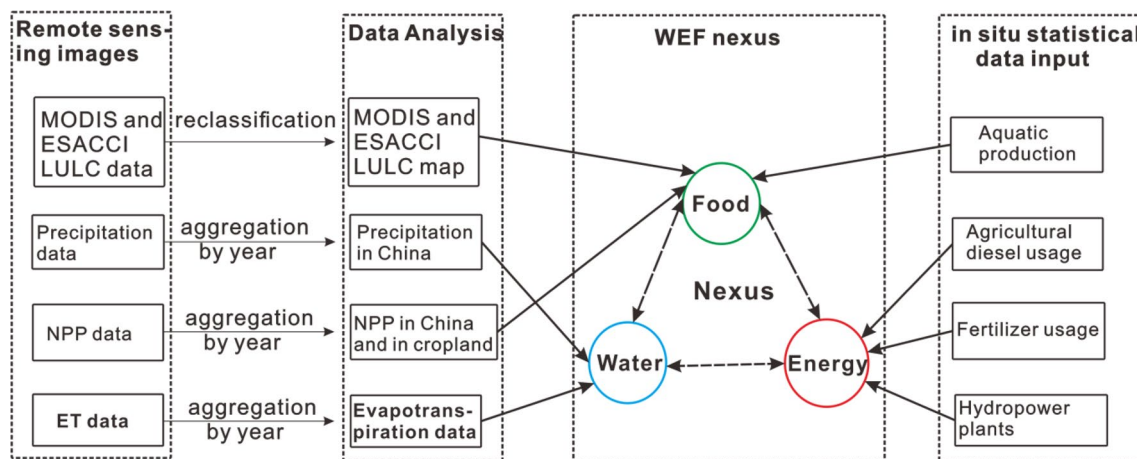
Fig. 1 Flowchart of the data processing and analysis in WEF nexus

Table 1 Reclassification of the LULC data obtained from MODIS

Old LULC classes	New LULC classes
Evergreen needleleaf forest	Forest
Evergreen broadleaf forest	
Deciduous needleleaf forest	
Deciduous broadleaf forest	
Mixed forest	
Closed shrubland	Other woody
Open shrubland	
Woody savanna	
Savanna	Grassland
Grassland	
Cropland	Cropland
Cropland/Natural vegetation mosaic	Vegetation mosaic cropland
Urban and built-up land	Urban
Barren	Barren
Water body	Wetland and water
Permanent wetland	
Permanent snow and ice	

Mosaic cropland: mosaics of small-scale cultivation 40-60% with natural tree, shrub, or herbaceous vegetation

yield of land (Jia et al. 2014). Besides, the pixel slopes are derived based on SRTM DEM data.

Sustainability evaluation methodology of the CCS/ CCUS technology

In order to investigate the sustainability of CCS/CCUS technology by the WEF nexus, the tradeoff energy–water consumption, the water consumption during the process of CCUS is analyzed first. After that, a typical coal-based power plant with a capacity of 630 MW in China is used as

an example to investigate the overall water consumption of power plant with and without consideration of CCUS. Thus, the water consumption of all coal power plants with the utilization of CCUS in China is estimated. In this work, two different carbon capture technologies (i.e., amine- and oxy-based) are considered. The carbon dioxide captured from the power plant is used as an alternative fluid for fracturing in the petroleum industry.

Sustainability assessment of CCFP in the WEF nexus and impacts on China's carbon neutrality

Effects of the CCFP implementation on China's carbon neutrality

Benefiting from the implementation of PES policies, especially the CCFP policy, China has significantly increased the natural carbon sink, leading the global greening process by the LULC management with the rapid growth in forestland cover area in the twenty-first century (Chen et al. 2019). The calculated total NPP in China based on MODIS images has significantly increased from 2.74 trillion kgC in 2001 to 3.18 trillion kgC in 2019 (see Fig. 2). The forestland cover area based on MODIS LULC products (Fig. 2) has increased from 81.3 million Ha in 2001 to 96.6 million Ha in 2019, with the much larger growth rate 11.3% in 2010–2019 compared with that of the first decade in 2001–2010.

Therefore, the implementation of CCFP and other PES policies in China is successful. The forestland including plantation forestland through CCFP and other PES policies in China produces about 4.04 billion tons of CO_2 sink per year during 2010 to 2016, equivalent to about 45% of the estimated annual anthropogenic emissions over that period

Table 2 Reclassification of LULC data obtained from ESACCI

No	Old LULC classes	New LULC classes
1	Cropland, rainfed	Rainfed crop (1)
2	Cropland, irrigated or post-flooding	Irrigation (2)
3	Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)	Mosaic cropland (3, 4)
4	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)	
5	Tree cover, broad leaved, evergreen, closed to open (>15%)	Forest (5, 6, 7, 8, 9, 10)
6	Tree cover, broad leaved, deciduous, closed to open (>15%)	
7	Tree cover, needle leaved, evergreen, closed to open (>15%)	
8	Tree cover, needle leaved, deciduous, closed to open (>15%)	
9	Tree cover, mixed leaf type (broad leaved and needle leaved)	
10	Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	
11	Mosaic herbaceous cover (>50%)/tree and shrub (<50%)	Other woody (11, 12)
12	Shrub land	
13	Grassland	Grass land (13, 14, 15)
14	Lichens and mosses	
15	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	
16	Tree cover, flooded, fresh or brackish water	Wetland water (16, 17, 18, 21, 22)
17	Tree cover, flooded, saline water	
18	Shrub or herbaceous cover, flooded, fresh/saline/brackish water	
21	Water body	
22	Permanent snow and ice	
19	Urban areas	Urban (19)
20	Bare areas	Barren (20)

Mosaic means that the area is small

Fig. 2 The total NPP and forest-land cover area in China based on MODIS from 2001 to 2019
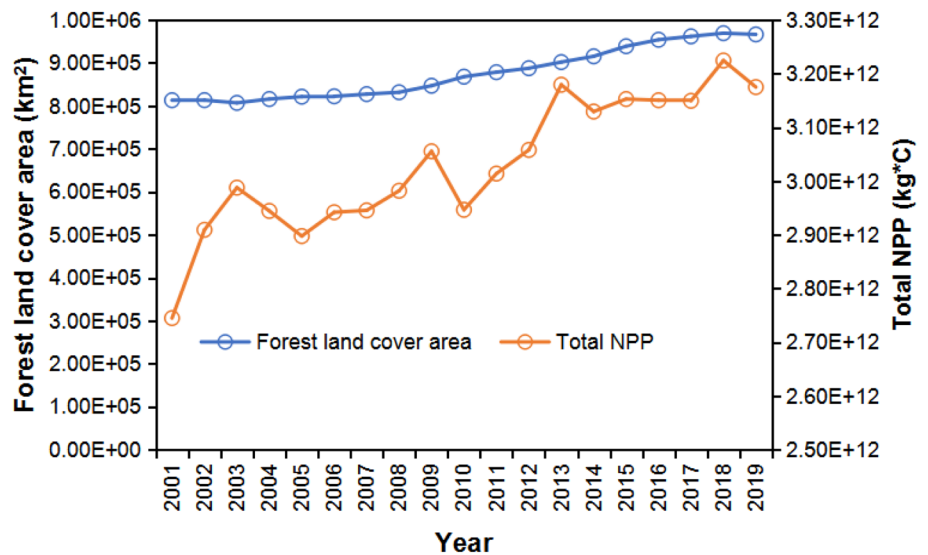
in China (Wang et al. 2020). Based on the 7th to 9th National Forest Inventory of China's State Forestry Administration, the plantation forest stock in 2008, 2013 and 2018 was 1.96, 2.48 and 3.39 billion m^3, respectively, with a much larger growth of 0.91 billion m^3 in 2013–2018 (annual growth rate of 0.182 billion m^3) compared with 0.53 billion m^3 in 2008–2013 (annual growth rate of 0.106 billion m^3).

Based on the successful experiences of CCFP and PES policies during 2013 and 2018 in China, if we continue with a constant annual growth of 0.182 billion m^3 for the plantation forest stock in 2019–2060, an estimated total growth of 7.462 billion m^3 during these 41 years due to the implementation of CCFP and other PES policies can satisfy the total plantation forest stock of about 10.852 billion m^3 in

2060. We take conservatively the total forest stock of 15.137 billion m³ and the corresponding CO_2 sink of 4.04 billion tons in 2013 (Wang et al. 2020) as reference, the sustainable implementation of CCFP and other PES policies could contribute a minimum CO_2 sink of 2.90 billion tons in 2060, which makes a great contribution to China's carbon neutrality by 2060.

Impacts of CCFP on cropland cover area and crop production

The CCFP is also called Grain for Green (GFG) program. Thus, a question rises "does the increased green leads to the decline in grain production?" To answer this question, the cropland cover area in China is calculated based on MODIS database, which shows that it first increased from 122.5 million Ha in 2001 to 124.8 million Ha in 2004, then it decreased to 122.1 million Ha in 2019 (Fig. 3), presenting an overall decrease trend. The irrigated cropland cover area also increased up to 66.23 million Ha in 2010, and then it decreased sharply to 64.93 million Ha in 2019.

The spatial variation of the cropland cover area between 2001 and 2019 is shown in Fig. 4, displaying the location of cropland conversion. It demonstrates that the vanished croplands in GFG program are mainly located at the eastern coastal provinces, and large portions of the newly converted croplands are distributed in northwestern provinces. In Hebei, Beijing and Guangxi provinces, a large amount of croplands are converted into other LULC types, while many newly generated croplands are observed in Shanxi and Xinjiang provinces.

The percentages of different land cover types converted from cropland in past two decades are calculated in a transition matrix (Table 3). 13.19% of the cropland in 2001 vanished and was converted to other land types in 2019, proving that the implementation of CCFP is successful. More than

68% of the vanished croplands are converted to woody, environmentally friendly land cover and thus greatly enhance the carbon sink in China. Among these 13.19% of vanished croplands, the converted grassland takes the largest percentage (8.3%), followed by mosaic cropland (3%) and urban land (0.98%). The mosaic cropland is defined as the mosaics of small-scale cultivation 40–60% with natural tree, shrub, or herbaceous vegetation. It indicates that some large-scale croplands are shrinkage or separated into small pieces of croplands. The rapid urbanization during 2001 and 2019 occupied some of these vanished croplands, which has no relationship with CCFP.

Since one of the goals of the CCFP is to convert cropland on steep slopes and low-production into forest or grassland, the average slope of the vanished and remained croplands are calculated in Table 3. The top three highest slopes of converted paths from croplands include forest, other woodland and grassland. Croplands with medium gradient of slope are not converted. Some croplands with high slope up to 6.58 shrank to small-scale farms. Most flattened cropland pieces converted to urban land with the average slope as low as 2.04.

To better understand the spatial distribution of the cropland conversion combined with the DEM variation, the vanished cropland layer is added to the ESRI Hillshade map (Fig. 5). It shows that the converted grassland is mostly distributed in the mountainous area with higher elevation in North China. The newly generated urban land is mainly located in Beijing, Tianjin and Shanghai. The converted mosaic croplands are primarily distributed in the South China mountainous area, especially in Guangxi and Guizhou provinces.

The balance between the increased carbon sink benefited from CCFP and food security is the key for the sustainability of CCFP. Food production is determined by the cropland area and cropland productivity. In this paper, the influences

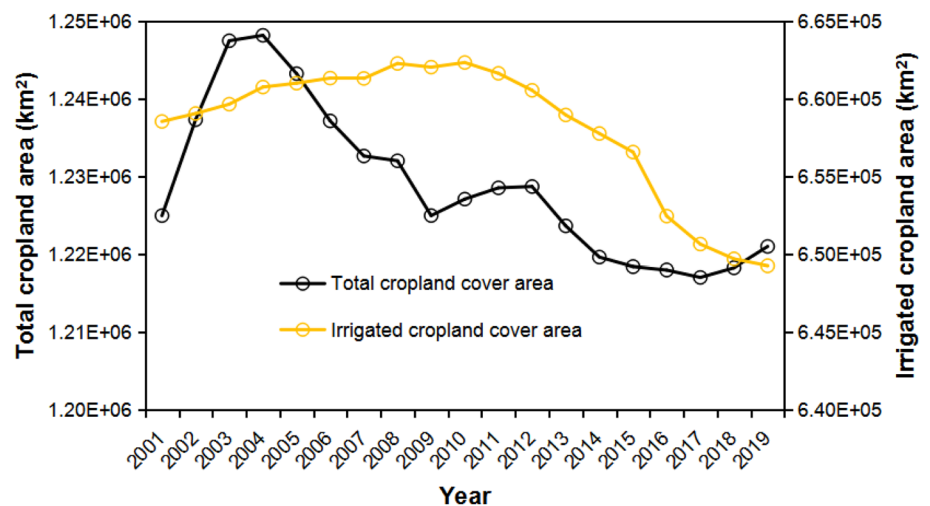**Fig. 3** The total cropland and irrigated cropland area based on MODIS between 2001 and 2019

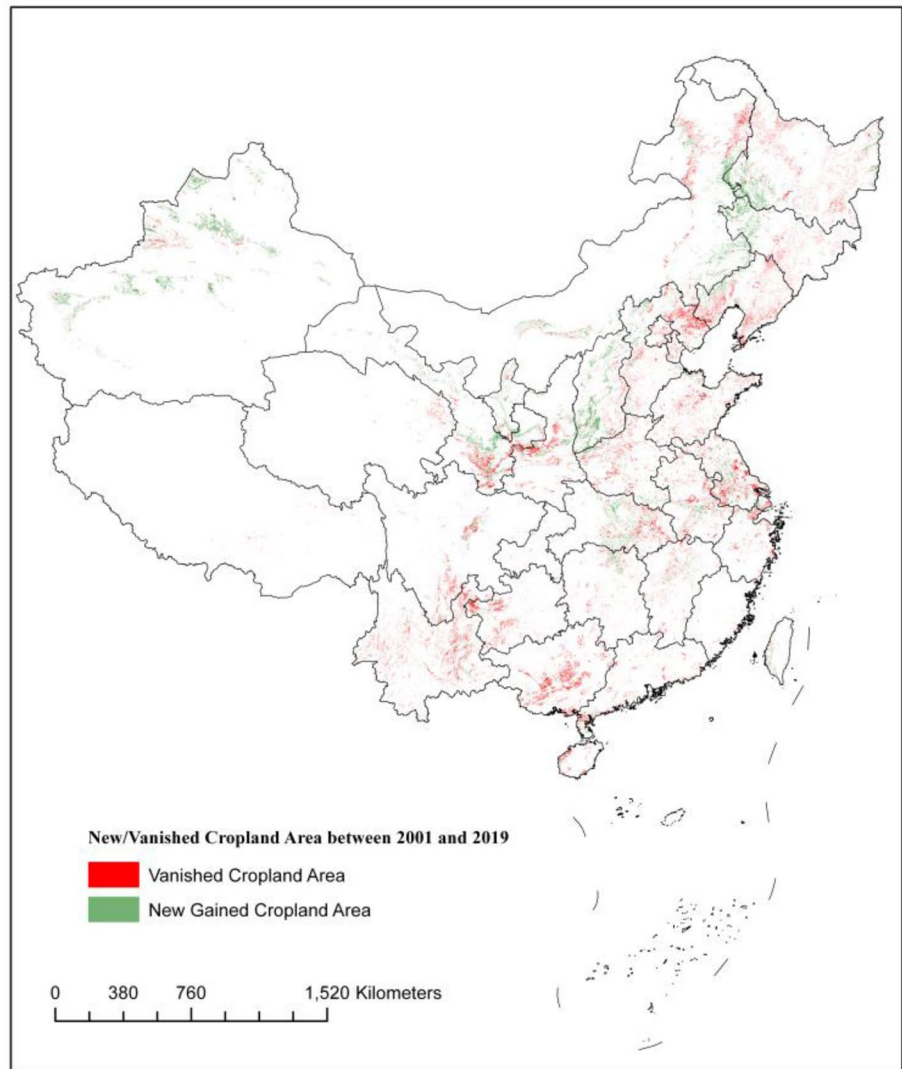**Fig. 4** The transition of cropland in China between 2001 and 2019

Table 3 The percentage of converted and remained croplands in 2019 with the calculated average slope based on the data of 2001

Land types	Percentage (%)	Slope
Forest	0.25	14.92
Other wood land	0.52	9.81
Grassland	8.30	7.52
Urban land	0.98	2.04
Barren	0.01	2.20
Mosaic cropland	3.00	6.58
Wetland and water	0.13	1.89
Remained croplands	86.81%	3.71

of the CCFP implementation on the cover area of irrigated cropland are studied, because the irrigated cropland is the main food production cropland in China. It has been proven that CCFP combined with urbanization has reduced the cropland cover area, but its impacts on the irrigated cropland are still unknown. The transition detection on irrigation cropland LULC between 2001 and 2019 based on European Space Agency (ESA) LULC products is carried out and a transition matrix is generated in Table 4. The result shows that CCFP has a small impact on the decrease of irrigated croplands cover area (less than 10%), while urbanization takes about 90% of the decrease in irrigated croplands. Through the implementation of CCFP, most converted croplands are rainfed cropland, rarely irrigated cropland, and thus it has a slight impact on the crop production.

Based on the national statistics, it is proved that the crop productivity in China has significantly improved within twenty-first century and leads to an increasing crop production trend even with the declined cropland cover area. Here, we combined the yearly NPP with time series cropland cover area to calculate the yearly average cropland production by remote-sensing assessment in Fig. 6. The result shows that

Fig. 5 The vanished croplands converted to other types of land (e.g., forest, grassland, urban, barren, mosaic cropland etc.) shown in ESRI world Hillshade layer in 2019 compared with that of 2001
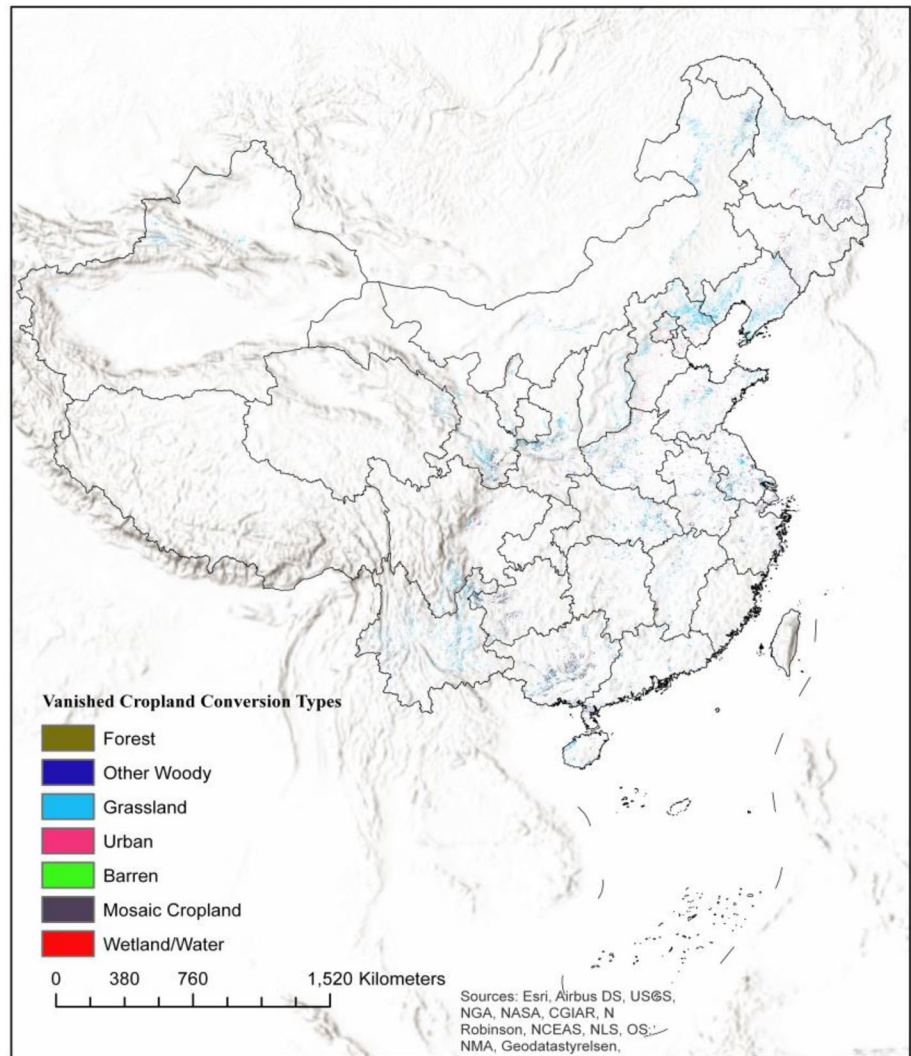

Table 4 The conversion of irrigated cropland between 2001 and 2019

Land types	Percentage (%)
Rainfed cropland	0.00
Mosaic cropland	0.00
Forest	0.18
Other wood land	0.01
Grassland	0.18
Wetland and water	0.07
Urban land	3.43
Barren	0.02
Remained croplands	96.10

the mean NPP significantly increased from 342.8 gC/m^2 in 2001 to 394.2 gC/m^2 in 2019. The same method is applied to evapotranspiration (ET) data as well, and it shows that the yearly mean ET on cropland significantly increased from 293.6 kg/m^2 in 2001 to 347.4 kg/m^2 in 2019 (see Fig. 6). The
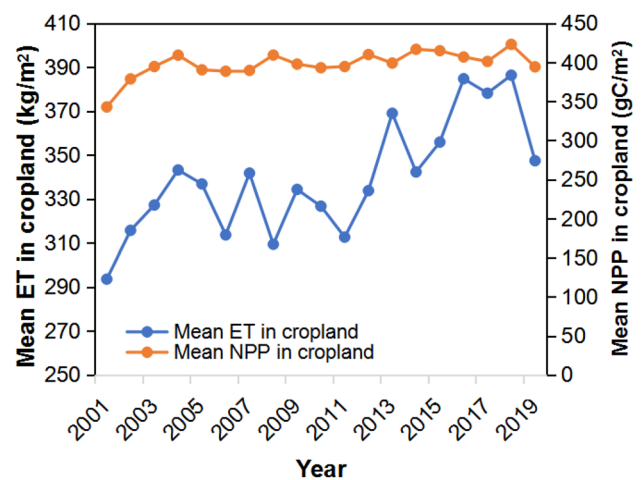

Fig. 6 Yearly mean NPP and ET in cropland between 2001 and 2019

growth in yearly mean NPP and ET on cropland indicates that the crops were more active and denser in agricultural units in 2019 compared with that of 2001.

Therefore, it can be demonstrated that the CCFP implementation does not lead to a food security issue as most of the vanished cropland belongs to steep slope rainfield cropland that does not affect the cover area of high-quality cropland like irrigated and low-sloped cropland. Furthermore, based on the report of China, the total crop production has increased around 50% between 2001 and 2019, which is much faster than the population growth rate. It can be concluded that there is no food security risk caused by the CCFP.

Sustainability assessment of CCFP in WEF nexus

The implementation of CCFP will change the LULC that may have great impacts on different types of natural resources, especially the water resources. Except for enhancing carbon sequestration, another goal of CCFP policy is

to reduce the soil erosion and improve the water storage. It is crucial to understand how the implementation of CCFP affects the water resources. The variation of cropland cover area driven by CCFP can alter the local water resource. We used the water production indicator (i.e., the precipitation minus evapotranspiration per unit area, representing the water storage capacity in the land) here to measure the trade-offs on water resources of CCFP.

We applied the precipitation and evapotranspiration data onto the converted cropland. To reduce the noise, we calculated the average water yield of 2001 and 2002 as the start point, and the average water yield of 2018 and 2019 as the endpoint. The mean water yield of each conversion land type is shown in Table 5. The water yield within the past two decades increased greatly in China, which may be caused by the glacier melting driven by global warming, the increased number of man-made dams and reservoirs, and the implementation of the CCFP policy. It is found that the most obvious increase in water yield occurred during the conversion of cropland to forest. The converted wood land and grassland also result in a growth in water yield. Therefore, the CCFP can improve water storage in soil and increase the carbon sequestration simultaneously.

Due to the reduced land degradation, soil erosion, and enhanced water yield driven by various PES policies, the water resources in China have increased significantly within the past two decades. The total precipitation has a significant increased trend, see Fig. 6. The permanent water surface area has risen considerably based on the analysis of satellite imagery, see Fig. 7. The flood risk is reduced by the CCFP which can stabilize the seasonal water by increasing water production (Li et al. 2019).

The vanished cropland by the implementation of CCFP altered the human-made resources input in agriculture at the

Table 5 Average annual water yield in different converted croplands

Directions	Average water yield of 2001 and 2002 (mm)	Average water yield of 2018 and 2019 (mm)
Forest	1930.793925	2552.026424
Other wood lands	590.3889883	648.6419978
Grassland	298.5884448	309.3717871
Urban land	753.9819376	1004.814147
Barren	− 210.7836648	− 77.0652744
Mosaic cropland	644.1336196	536.8922755
Wetland and water	1673.221434	1898.60465
Remained cropland	351.7852107	440.7938234

Fig. 7 Permanent and seasonal water surface area, and total precipitation in China between 2001 and 2019
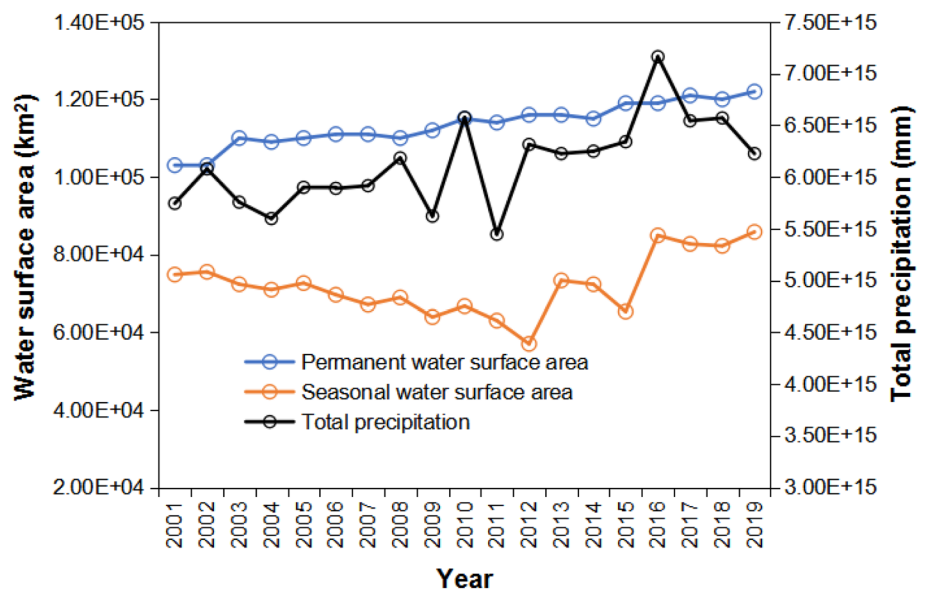
same time. Energy input is one of the critical inputs in crop production, including the supply of agricultural machine power, fertilizer input, etc. To assess trade-offs of CCFP, it is crucial to understand the variation of energy input in the past two decades. The agricultural diesel usage has increased significantly from 14.85 Mtons in 2000 to 20.03 Mtons in 2018 (Fig. 8). The fertilizer input in cropland has increased from 42.54 Mtons in 2000 to 54.04 Mtons in 2018 in Fig. 8. The energy input in agriculture increased fast in the past two decades in China, which is partly due to the rapid growth of economics. The converted cropland-triggered productivity demand after the implementation of CCFP is another important reason. Fortunately, the dramatic growth of fertilizer input may not lead to a contradiction to carbon sequestration intention, but the manufacturing of fertilizer will release CO_2 into the atmosphere. The N fertilizer has declined significantly after 2014 (Fig. 8). Therefore, the trade-offs of C-N to greenhouse gases are not required to be considered.

The trade-off of CCFP in WEF nexus seems to be clear, showing a strong pro in Water and small cons in Food and Energy. However, the WEF nexus is an integrated resource system, and the chain effect occurs everywhere. For instance, the increased water resource results in more hydropower station in the rural area. The number of hydropower stations with the capacity less than 50,000 kW increased from 44,815 in 2010 to 46,515 in 2018 in the rural areas, and the capacity increased from 59.2 million kW in 2010 to 80.4 million kW in 2018. Increasing water resources can not only boost the generation of electrical energy, but also improve

the food production by fishery. The enriched inland freshwater resource results in more aquatic production, which was doubled from 15.6 Mtons in 2001 to 32.0 Mtons in 2019. The freshwater aquatic production increased much more rapidly than the marine aquatic output, which was 22.3 Mtons in 2001 and increased up to 32.8 Mtons in 2019. More water resources can also enhance the irrigation intensity and thus improve the crop productivity. Therefore, it is concluded that the CCFP is sustainable because the pros of water production and carbon sequestration are remarkable and the cons are deductible.

The remote sensing-based assessment in CCFP analysis provides a broader view on the sustainability of CCFP in WEF nexus. Instead of dealing with the statistical numbers, it provides another perspective to evaluate the spatial distribution and slight changes caused by policy implementation. For instance, the results in this paper show that the cropland conversions are distributed at some specific locations but not all over the country. The CCFP policy implementation should be insisted based on the assessment in this paper. However, some issues need to be noticed. First, there is great spatial difference in cropland conversion, showing that some provinces have very limited croplands converted. Secondly, the shrinking of large agricultural land blocks combined with the increase of small land blocks (e.g., mosaic natural vegetation and cropland) may lead to a pseudo-increasing of national cropland and the food security issue. Third, more carbon emission may occur when the converted land is cultivated and farmed after the subsidies stop.

Fig. 8 The usage of agricultural diesel, total fertilizer, and N fertilizer between 2000 and 2018 in China
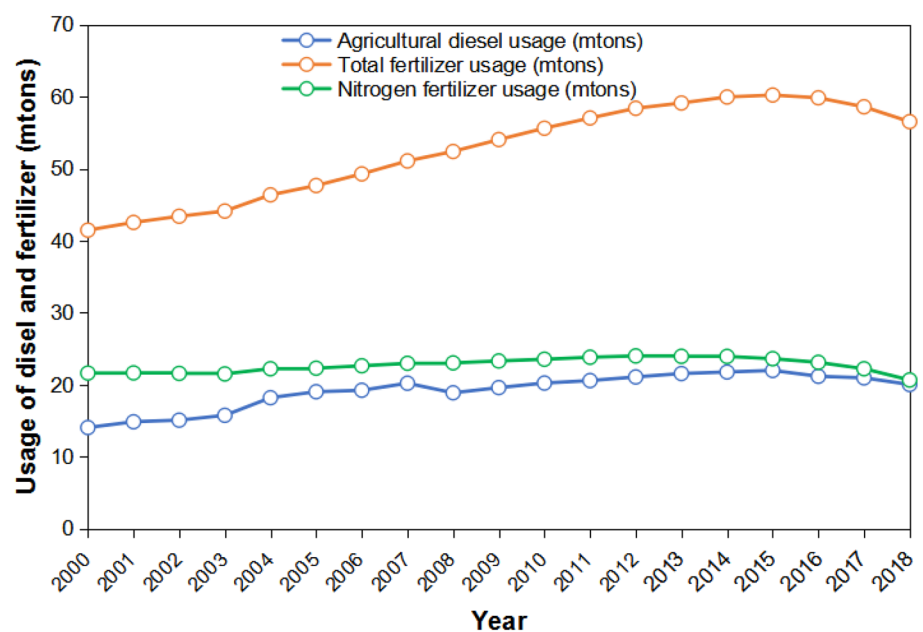
Sustainability assessment of CCS/CCUS technologies in the WEF nexus and impacts on China's carbon neutrality

### Application status of CCS/CCUS technologies in China

China started the research on CO_2-EOR technology in the 1960s in Daqing oilfield. Afterward, a series of pilot-scale CO_2-EOR projects can be found in Jilin oilfield, Dagang oilfield, Shengli oilfield and Liaohe oilfield (Liu et al. 2017; Cao et al. 2020), proving that the CO_2-EOR technology has been successful in increasing the oil recovery at different levels. The studies on CO_2-ECBM started at the end of twentieth century and there is an important pilot-scale project in Qinshui Basin. In 2010, the first full chain (from CO_2 capture of the coal chemical industry to CO_2 sequestration in the saline formations) CCS project with the target of 0.1 Mtons of CO_2 injection was settled in the Ordos Basin in China, and the total CO_2 storage amount was about 0.3 Mtons (Wang et al. 2018). However, the researches in the fields of CO_2-EGR, CO_2 enhanced shale gas recovery (CO_2-ESG), etc., are at the very preliminary stage (Liu et al. 2020). Until the end of 2017, about 26 projects of CCS or CCUS had been carried out in China, including 14 CO_2-EOR projects in oilfields of Daqing, Jilin, Shengli, Zhongyuan, Yanchang, etc. There are also some projects related with the industrial

conversion of captured CO_2 but not used for underground geological sequestration (Liu et al. 2017). However, the massive water consumption in the carbon capture process together with energy production (Li et al. 2016) sparks the controversy on potential water risk related to CCU/CCUS technologies affiliated with energy production. Therefore, the potential of water resource risks associated with the energy production and the consumption of water during the CCS/CCUS process are discussed to analyze whether the CCS/CCUS is beneficial in the energy production industry in the long term.

Analysis of potential water resources risks in energy production of China

Figure 9 shows the total energy related water consumption mapped over regional water risk in China. Ten sectors are involved in the analysis of water consumption on energy production, including the biofuel feedstock production, energy processing including biofuels and oil, energy production including oil, gas, coal, uranium, and unconventional oil and gas, hydroelectric and thermoelectric power (Tidwell and Moreland 2016). The watershed and energy-related water consumption locations have high energy-water risk. It can be seen that the northeastern China has the highest concentration of watersheds at energy–water risk. There are in total 1630 watersheds in China, 764 of which have water risks. Regarding the energy-related water consumption, there are 440 watersheds and 54%

Fig. 9 Total energy related water consumption mapped over regional water risk in China (after Tidwell and Moreland 2016)
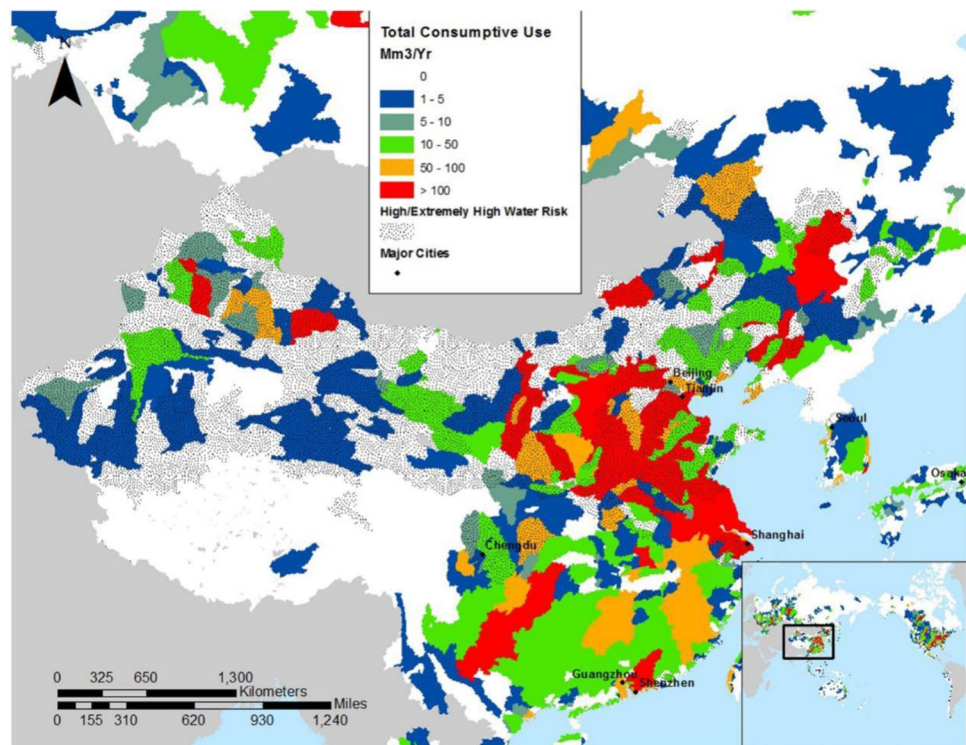
of them have energy–water risks (Tidwell and Moreland 2016). Generally, it can be concluded that China has a high risk of water consumption related with energy production. Therefore, it is suggested to mitigate the water risk related with energy production by using the technologies of CCUS, such as utilizing CO_2 for enhancing oil recovery.

Water consumption in CO_2 capture process

The fossil fuel-based power plant is a main source of CO_2 emissions. Figure 10 presents the water consumption in four kinds of fossil fuel power plants with and without CO_2 capture process, including subcritical and supercritical pulverized coal-fired (PC) power plants, integrated gasification combined cycle (IGCC), and natural gas fired combined cycle (NGCC). It shows that the water consumption increases from 31% to ~ 91% when CO_2 capture is implemented. Therefore, the CO_2 capture is the largest contributor to water consumption during the processes of CCS/CCUS. Actually, the cost of CCS technology is also dominated by the process of CO_2 capture and gas separation, which is about \$55 to \$112 per ton of CO_2 (Gislason et al. 2014). In order to decrease the energy and water consumption, it is suggested to make use of the waste heat through heating water. After that, the heated water can be used for power generation. In this way, the emission of water vapor and overall water consumption can be reduced.

Water consumption in CO_2 utilization process

CO_2 can be used to enhance water recovery (CO_2-EWR). The Gorgon CCUS project located in the northwest of Australia is an example to illustrate the water consumption of CO_2-EWR. There are two periods in this project, including the construction period from 2010 to 2015 and the operation period from 2015 to 2050. In the life cycle of the Gorgon project, more than 120 Mtons of CO_2 will be injected into the Jurassic saline reservoir at a rate of about 3.8 Mtons per year. Meanwhile, four pumping wells are implemented to manage the formation pressure and produce saline water to meet the demand of water consumption during the life cycle of this project (Flett et al. 2008). The water consumption and supply during the construction and operation phases are shown in Fig. 11 (Li et al. 2016). It can be seen that the water consumption is very high at the beginning of construction, and the water supply cannot meet the demand, which is obtained from the treated wastewater and the saline water with a reverse osmosis (RO) process. While the water consumption is decreased and can be met by water supply during the rest construction and operation periods. For example, the total of potable and service water demand is 960 m^3/d, while the water supply is approximately 1,500 m^3/d in the operation phase. Therefore, it can be calculated that about 6.9 million m^3 of net water can be attained during the 35 years of operation. Generally, it can be concluded that CO_2-EWR is an efficient strategy to produce water and store CO_2 simultaneously.

Fig. 10 Water consumption in fossil fuel based power plants with and without different types of CO_2 capture technologies (Li et al. 2016)
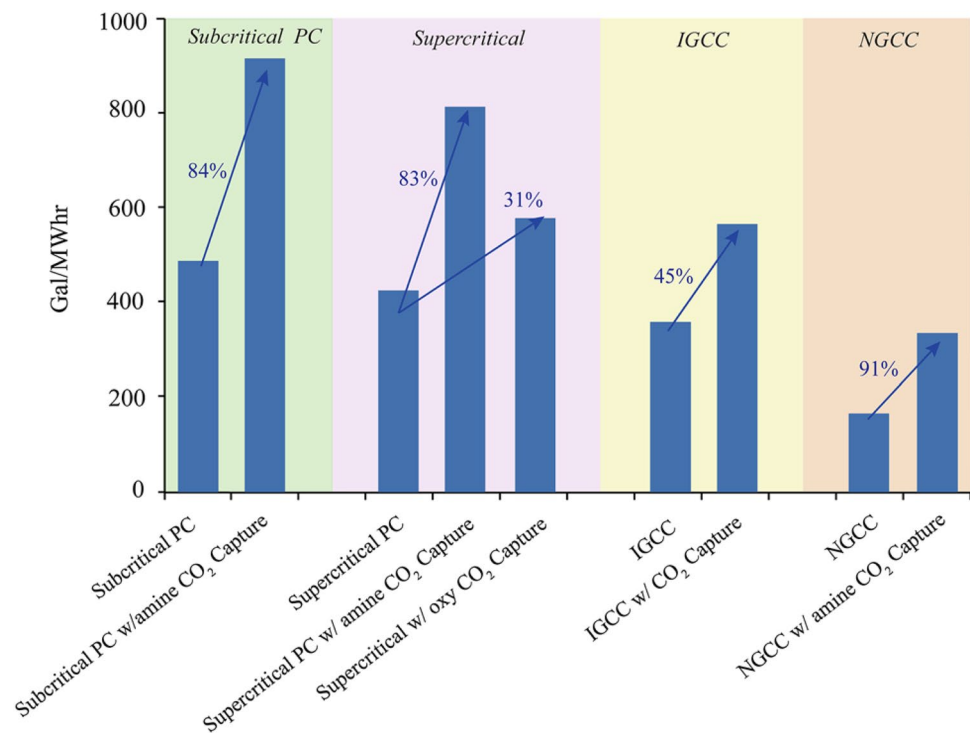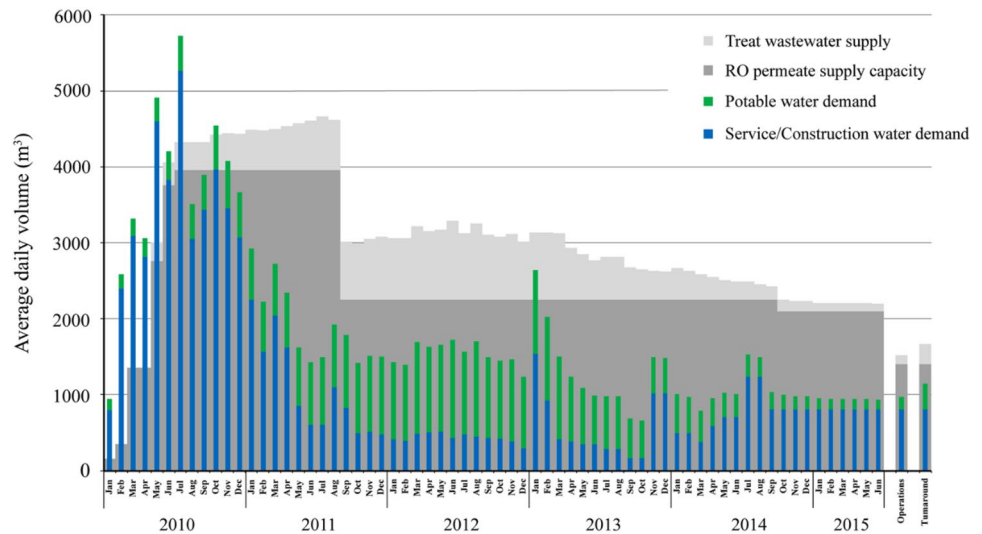
Fig. 11 Water consumption in Gorgon project (Li et al. 2016)

Water consumption related with energy production and potential application of CCUS

Based on the fuel production categories with water consumption factors estimated by Spang et al. (2014), the water consumption related with the energy production in China is shown in Table 6. The total water consumption related to energy production in China is 4.93 billion m^3, which is dominated by coal production followed by oil production, with the water consumption of 4.19 billion m^3 and 0.702 billion m^3, respectively. It should be pointed out that the ratio of shale gas production to conventional gas production is 11.6%, while the water consumption of shale gas is about half of the conventional gas, which illustrates that abundant water is consumed during the hydraulic fracturing process in the exploitation of shale gas.

The exploitation of shale gas usually consumes large amounts of water resources in hydraulic fracturing, which is necessary in the ultra-low permeability of shale reservoir. It is reported that the water consumption in the Marcellus shale gas reservoir is about 20,000 m^3 per well over the whole
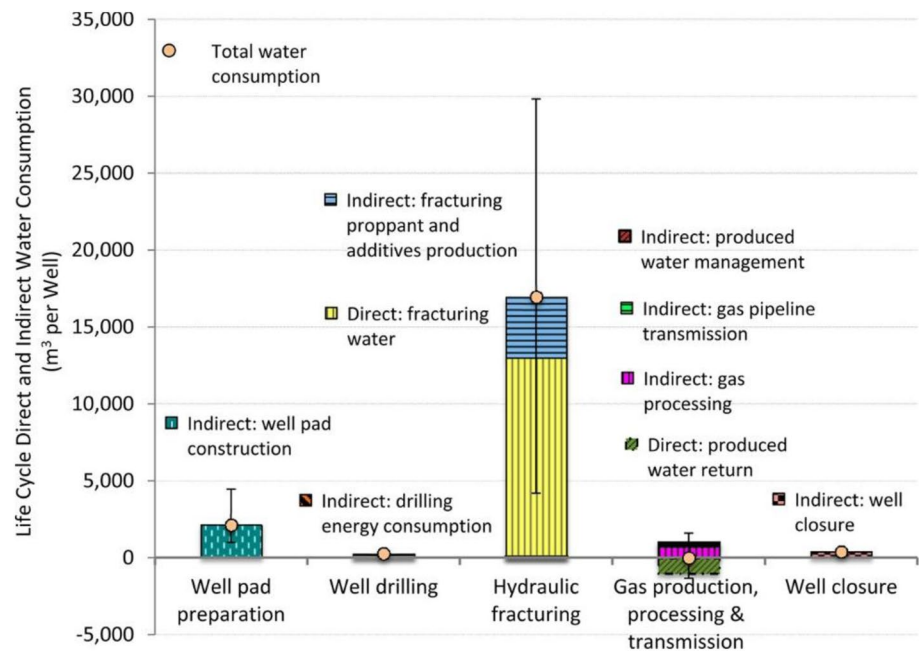
life cycle, in which 65% of water is consumed at the well site and 35% of water is consumed across the water supply chain (Jiang et al. 2014). The water consumption across the life cycle of a shale well is shown in Fig. 12. It can be seen that the water consumption, especially the direct consumption of fracturing fluids is the dominating part in shale gas production.

China has the largest shale gas reserves in the world, with a cumulative proved reserve of more than 6.5 trillion m^3 estimated at the end of 2019. While the exploitation of shale gas in China is still at the primary period, with a production of only 20.04 billion m^3 in 2020, which is far less than that of the USA. Due to China's high degree of dependence on foreign oil and natural gas, i.e. 70.8% for oil and 43% for natural gas in 2019, promoting domestic oil and gas production is the basic energy strategy. Therefore, it can be inferred that the water consumption would increase dramatically with the large-scale exploitation of shale gas in China (Zhou et al. 2019), which may lead to high water risk. To address this problem, it is suggested to use CO_2 as working fluid for hydraulic fracturing in shale gas production. If the

Table 6 Water consumption related with fossil fuel energy production in China

Energy category	Water consumption factor (m^3/GJ)			China output in 2020	Heat values (MJ/kg)	Average water consumption (billion m^3)
	Spang et al. (2014)			National Bureau of Statistics 2021	World Nuclear Association 2021	Calculated
	Min	Max	Mean			
Coal	0.006	0.242	0.043	3.9 billion tons	ca. 25 (25)	4.19
Conventional oil	0.036	0.14	0.081	0.195 billion tons	42~47 (44.5)	0.702
Conventional gas	0.001	0.027	0.004	172 billion m^3	42~55 (48.5)	0.0239
Shale gas	0.003	0.221	0.017	20 billion m^3	42~55 (48.5)	0.0118
Total						4.93

Fig. 12 Estimated water consumption for a shale gas well. Error bars represent the limit of 90% confidence intervals of water consumption from each life cycle (Jiang et al. 2014)

Sustainability of CCUS in coal-based power plants and impacts on WEF system

The water consumption of power plant with and without consideration of CCUS will be investigated based on a typical coal-based power plant in the central of China (Liu and Zhai 2014). The installed capacity of the power plant is 630 MW. In 2013, the standard coal equivalent consumed by the power plant is 1,916,242.87 tons, with the power generation of 4,010.57 million kWh and the CO_2 emission of 3,616,269.76 tons, in which 3,600,333.76 tons of CO_2 are produced during the process of stationary coal combustion and 15,936 tons of CO_2 are produced during the process of desulfurization.

The CO_2 captured from the power plant can be used as an alternative fluid for fracturing. Based on the aforementioned discussion, the water consumption in hydraulic fracturing dominates the overall water consumption in shale gas or unconventional oil or gas production. Regarding the CO_2-based hydraulic fluids, the water is only consumed at the initial compression period, which is much less than that of water-based hydraulic fluids. Generally, compared to conventional water-based hydraulic fracturing, the water consumption can be decreased by 80% per unit energy production when the CO_2-based fracturing is implemented (Wilkins et al. 2016). According to Liao et al. (2020), the permeability of hydraulic fractures generated by water and CO_2 with the same injection mass can be comparable. Thus, 3,600,333.76 tons of water can be saved if the CO_2 captured

CO_2 fracturing technology is implemented, the water consumption will be greatly decreased.

from the coal power plant is utilized in reservoir stimulation. It should be pointed out that the impact of CO_2 storage on water consumption is negligible, but it can save a large amount of water by replacing the traditional water-based fracturing technology. Generally, the water consumption of the power plant with and without consideration of CCUS is shown in Fig. 13.

Different types of CO_2 capture technology have great impacts on the water consumption. It shows that the overall water consumption increases by 2.84 million m^3 per year when the amine-based solvents is applied to separate CO_2. However, the water consumption reduces by 1.19 million m^3 per year when the oxyfuel capture method is
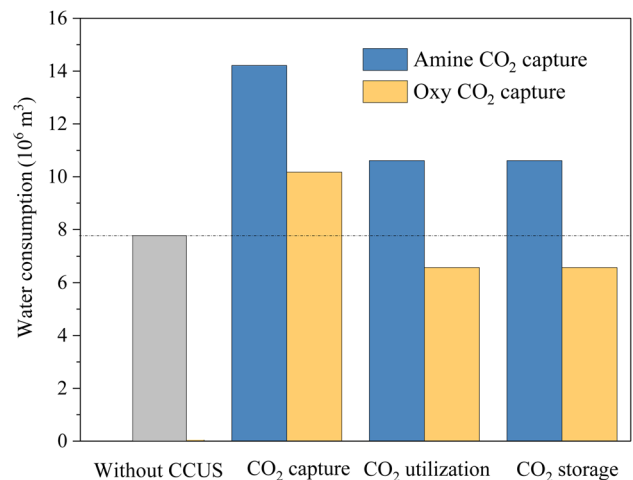

Fig. 13 Water consumption per year of the 630 MW power plant with and without consideration of CCUS

used. China has the largest installed capacity of coal-based power stations in the world, which is 1.095 billion kW at the end of 2020, meaning that about 20.73 billion m^3 of water consumption can be reduced per year if the CCUS technologies are implemented for all coal power plants in China. It can be inferred that the energy can be produced in some regions that are lack of water. The CCUS technologies can not only reduce the water consumption but also increase the energy production.

Based on the water consumption factor of oil (Spang et al. 2014), it can be calculated that the saved water due to the utilization of CCUS in the 630 MW power plant per year can generate 330 thousand tons of oil (i.e., equivalent to 14.7 million GJ of energy). Considering that the food can be linked to energy through the utilization of food crops as feedstock for biofuel production, the produced energy caused by the utilization of CCUS can decrease the consumption of food. Furthermore, the water consumption of biofuel production can be saved. For instance, considering that the water consumption for the generation of ethanol is $41.8 \sim 124.8$ m^3/GJ (Rulli et al. 2016), it can be calculated that additional $0.614 \sim 1.83$ billion m^3 of water can be saved with the utilization of CCUS.

It should be mentioned that the CO_2-based fracturing technology has great advantage than that of water-based case in water saving but requires much more energy consumption (Wilkins et al. 2016). This is caused by the compression and separation of CO_2 in the power plants, and the incremental energy required for CO_2 transportation phase. With the development of CO_2 fracturing technology, it can potentially achieve a lower net energy consumption.

Simultaneously, the injected CO_2 can be sequestrated during the CO_2 fracturing process, which is beneficial for mitigating atmospheric CO_2 emissions and protecting the environment. In comparison with CCUS, the CCS technologies can contribute to much more geological CO_2 sequestration due to the widespread feasibility targeted for China's carbon neutrality by 2060. China has been the largest emitter of CO_2 since 2006, currently responsible for approximately 28% (net equivalent CO_2 emission of 9.8 billion tons = gross equivalent CO_2 emission of 14.2 billion tons—CO_2 sink of 4.4 billion tons) of global CO_2 emissions in 2019. President Xi Jinping stated on September 22, 2020 that China will reach the peak of CO_2 emissions before 2030 and achieve carbon neutrality by 2060. The estimated peak of net equivalent CO_2 emissions before 2030 is about 11.0 billion tons. It is very difficult to achieve the carbon neutrality target by 2060 without widespread application of CCS/CCUS technologies for geological sequestration of CO_2 and the sustainable implementation of CCFP and other PES policies in 2019–2060.

Conclusions

In this paper, the sustainability of two typical carbon sequestration pathways (CCS/CCUS and CCFP) is analyzed and evaluated by WEF nexus in context of China's carbon neutrality by 2060. Some conclusions can be drawn as follows:

1. The implementation of CCFP policy has led to the decrease in the cropland in China but no food security issue emerges because CCFP has small effect on the decreases of irrigated croplands cover area (less than 10%), while 90% of the decrease in irrigated croplands is induced by urbanization.

2. A sustainable implementation of CCFP and other PES policies in 2019–2060 could reach an estimated total growth of 7.462 billion m^3 in comparison to that in 2018 and the total plantation forest stock of about 10.852 billion m^3 in 2060, with a corresponding minimum CO_2 sink of 2.90 billion tons in 2060.

3. Different types of CO_2 capture methods have significant impacts on the water consumption. The overall water consumption increases by 2.84 million m^3 per year when the amine-based solvents to separate CO_2 method are used. However, the water consumption reduces by 1.19 million m^3 per year when the oxygen-enriched combustion capture method is used in China.

4. More energy may be produced from the shale gas, oil and natural gas reservoirs with the utilization of CCUS when the water is replaced by CO_2, which is especially applicable for the regions facing lack of water resources. Furthermore, the consumption of food can be reduced due to the decreased demand of biofuel production. Overall, the utilization of CCS/CCUS can be beneficial for WEF and China's carbon neutrality by 2060.

5. The integrated impacts of CCFP and CCS/CCUS on water, food and energy resources are understood by WEF nexus assessment, implying that the trade-off is acceptable. The geological CO_2 sequestration through the large-scale application of the CCS/CCUS technologies CCS/CCUS as well as the CO_2 natural sink through the sustainable implementation of CCFP and other PES policies in 2019–2060 are necessary and play a decided roll for China's carbon neutrality by 2060.

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Authors and Affiliations

Yachen Xie[1,2] · Zhengmeng Hou[3,4] · Hejuan Liu[5] · Cheng Cao[6] · Jiaguo Qi[1,2] [ID]

[1] Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48824, USA

[2] Department of Geography, Environment and Spatial Sciences, Michigan State University, East Lansing, MI 48825, USA

[3] Research Center of Energy Storage Technologies, Clausthal University of Technology, 38640 Goslar, Germany

[4] Institute of Petroleum Engineering, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany

[5] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

[6] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China