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Modeling water-energy-food nexus for planning energy and agriculture developments: case study of coal mining industry in Shanxi province, China

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Contents

Abstract

As the main energy in China, coal has been the guarantee for the sustainable and rapid development of the economy. It will remain to be the guarantee for energy security in China for a very long time. However china's reliance on coal has raised a number of urgent environmental, economic, and social issues. Despite the fact that CO_2 emissions and air pollution are well known, land deterioration and high water consumption are less evident, but not any less severe. And those issues are a threat to energy, water, and food security in China.

The Chinese government has actively started addressing the problems related to the coal mining industry. Due to the isolation of the administrations and interdependencies among the problems, the issues are not being dealt with in a coordinated way. It is imperative to find a systemic way to analyze and deal with the development of the coal industry under the energy, water, and food security interdependencies. Herein, a model which is spatially detailed and could support the coal and agriculture production strategy under several resource and security constraints, has been developed.

Through scenarios analysis, numerical experiments are carried out to illustrate the coal and agriculture productions under varying availability of water resources. In a visible way, we select some of the result to prove that the model can help select the optimal location and technologies sets of coal and agriculture production accounting for energy-food-water-environmental security constraints.

Key words: coal production, agriculture, energy security, food security, water security, model

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Modeling water-energy-food nexus for planning energy and agriculture developments: case study of coal mining industry in Shanxi province, China

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1. Introduction

As the main energy source enabling energy security in China, the rapid growth of coal production and its competition with agriculture for limited land and water resources raises questions about energy, water, and food security. Energy, water, and food security is the basis for the sustainable development; and it draws a lot of attention of the researchers and policy-makers since the coal industry has, is, and will continue to play an indispensable role in China's economy. Currently China produces and consumes almost as much coal as the rest of the world combined. It has become the world's top coal producer, consumer, and importer, accounting for 46% of global coal production and 49% of global coal consumption (EIA, 2014a). In 2013, coal ensured the vast majority, 66% of China's total energy consumption (NBSC, 2014). It is expected that the share will fall to 63% by 2020 and to 55% by 2040 as a result of improved energy efficiency and China's goal to increase its environmental sustainability. However, the absolute coal consumption is expected to increase by over 50% during the 25-year period (EIA, 2014b). In this section we discuss the motivation of the study, particularly the interdependencies among different factors which define the structure of the developed in section 2 model enabling the integrated analysis of coal industry developments in the presence of joint energy-food-water- environment security goals.

1.1 Impact of coal industry in China

China's reliance on coal has raised a number of urgent environmental, economic, and social issues. Traditionally, coal mining is associated with serious air pollution. The high sulfur content of most of the Chinese coal leads to the high level of sulfur dioxide (SO_2) emission, especially from coal burning power plants. The SO_2 emissions not only aggravate respiratory and heart problems, but also contribute to the toxification of water resources and desertification through acid rains. Coal is also the culprit of CO_2 emissions. Coal consumption was responsible for three quarters of China's CO_2 emissions from fossil-fuel combustion in 2012 (PBL, 2013). In 2013, global CO_2 emissions were dominated by emissions from China (28%), which also comprised the most of the 2013 emission changes (58% increase) (GCP, 2014)

Air pollution and emissions are not the only major problem of the coal industry. Less evident, but not less severe is land deterioration. Over the last 20 years, coal mining seriously contributed to China's problem of losing the farmland. The amount of farmland destroyed by coal mining has reached 692 thousand hectares (Hu et al., 2014). Chinese coal production is dominated by underground mining, which accounts for nearly 95% of the coal output. The underground mining causes land subsidence, which leads to severe conflicts between farming and mining. Every Mt of extracted coal has been estimated to result in 20 ha of subsided land. According to statistics, subsided land is approximately one million hectares in the country and it is increasing at the annual rate of about 70 thousand hectares (Bian et al., 2010). Intensification and expansion of coal mining and the resulting subsidence of farmland became an urgent issue as more than 40% of the total farmland area overlaps with coal resources in China. Apart from the subsided land, there are more than 15 thousand hectares farmland occupied by coal gangue, which is the left solid waste in the process of coal mining. Annual rate of gangue extraction is about 150-200 million tons (Guo et al., 2011). At present, the main disasters of coal gangue are farmland loss, soil, air and water pollution, land degradation, spontaneous combustion.

China has about 21 percent of the world's population, which is supported by only about 9% of the world's farmland (FAO, 2010). While limited farmland has always been a problem, the industrialization speeded up agricultural land conversion leading to food shortages in China. Efforts to expand the farmland are costly and have low success. Therefore, China cannot afford to sacrifice its farmland for the sake of economic development. Alarming signs that the Chinese food supply is at risk are manifested by lowering grain self-sufficiency, increasing food imports and prices. Compare with 2012, the imports of corn, wheat, and rice have doubled in 2014. (WPI, 2014; Fan et al., 2011) and the prices for agricultural commodities continue to rise, which lifts up the consumer price index (CPI) and the risk of food security of the poor people (Lv and Ji, 2014). Degradation of agricultural land and shrinking farming activities is a major cause of social problem in rural areas, areas depopulation, migration, and unemployment.

To most alarming and urgent warning associated with the coal industry belong high water consumption and pollution. Coal-based industries - mining, washing, chemical production and power generation -are all extremely water-intensive (Pan et al., 2012; Greenpeace, 2012), what exacerbates the problem of scarce water resources in China. In China, water resource per capita comprises only about 1.7 thousand m^3, barely above the United Nations' water scarcity index (WRI, 2014). What worsens the situation is a huge mismatch between the water resources and the location of coal reserves. About 53% of China's coal reserves locate in water scarce regions and 30% are in water stressed regions (Fig.1) (TNI, 2014). In order to reduce the transportation costs, the coal-fired power generation capacity and coal-to-chemical industry are usually located closely to coal mines, what exacerbates the industry's environmental impacts on already stressed water resources. Water resources face strong competition among the water users (coal-based industries, hydropower, households, agriculture, and heavy industry) and their uncoordinated activities can substantially increase water stress in the areas.

Water shortage may become more prevalent and severe due to changing precipitation patterns because of weather variability and climate change (Hagemann et al., 2013); especially, in such provinces as Shanxi, Inner Mongolia, which already have high water scarcity risk. Unstable or restricted water provision and the conflict between the coal-based industry and other water users over the access to limited water resources may lead to increasing risks of potential power grids blackouts due to energy underproduction, as it happened in Texas in 2011. A drought in Texas placed exceptional load on the power grid, and it was possible to avoid blackouts only by placing restrictions on farmers and ranchers with senior water rights, showing the tension on the water resources from the competing demands of primary agriculture and energy (Faeth, 2013).

1.2 Governmental interventions

The Chinese government has actively started addressing the problems related to the coal mining industry. The government has introduced a number of policies to impose a mandatory cap on the coal consumption (MEP, 2011; MEP, 2012; State Department, 2013; National Energy Administration, 2014). It is being considered to impose an absolute cap on the greenhouse gas emissions from 2016 (Adam and Tania, 2014), which means that the power plants will have to undertake more efforts towards emissions reduction.

At the end of 2013, the Ministry of Water Resource (MWR) announced the plan of water for coal, which pertains to control the total water use by coal bases and power generation (CWR, 2014). On 17 July 2014, the Notice on Environmental Impact Assessment of Coal-Electricity Base, which requires water approvals for new coal mining capacities, was issued by the Ministry of Environment Protection (MEP, 2014). The National Energy Agency announced a notice on the coal-to-oil and coal-to-gas projects, according to which the approval and ratification of the projects is possible only after detailed analysis of water resource availability and water demand of other water users, i.e., agriculture, households, industries, etc. New projects are implemented only if they do not compete for water with other economic activities in the region.

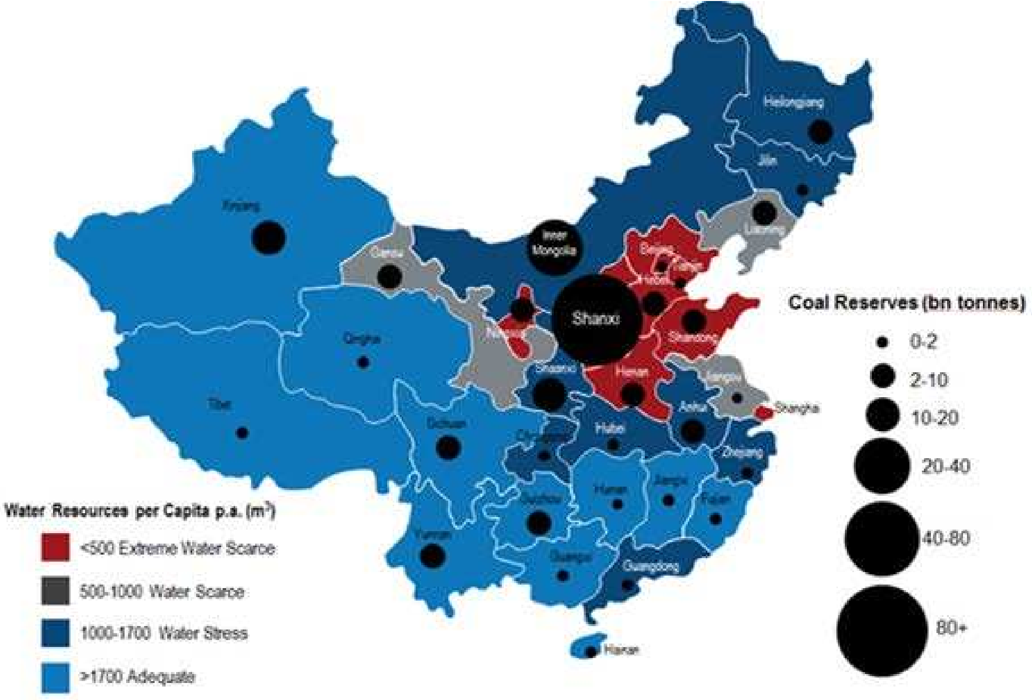

Fig.1: Geographical mismatch between availability of water and coal mining industries (Source: China Water Risk)

In the beginning of 2014, the Government stressed the priority to improve rural livelihood and emphasized the target of a minimum farmland in order to provide safe domestic grain production, i.e., to ensure food security (State Department, 2014). The adopted laws and recommendations now oblige coal mining enterprises to make re-equipment and upgrade, first of all, to ensure efficient use of natural resources for secure energy, water, and food supply.

1.3 Research question

The action, which the Chinese government has taken in the past to overcome the negative impacts from the coal industry, were only partially successfully to address the outlined problems as they did not take an integrated approach. The issues are dispersed among different ministries and administrations and are not being treated in a coordinated way. It is imperative to find a systemic way to analyze and deal with the development of coal industry under the energy, water, and food security interdependencies.

While many studies have been done on air quality and greenhouse gas emissions from coal industry (Zhang and Smith, 2007; Van Dijk et al., 2011; Zeng et al., 2013; Tang et al., 2014; Yu et al., 2014), the problems related to the misuse and overexploitation of natural resources in China, in particular, water and land, have not yet received adequate attention. Few studies on the assessment and management of the impacts and the relevant technologies are available in (Niu et al., 2014; Xiao and Hu, 2014; Sun et al., 2012). Some rather descriptive studies (Pan et al., 2012; WRI, 2014) treat natural resources (land and water) as constraints for coal industry in China. However, to our best knowledge, there are no studies, which analyze the problem in an integrated way accounting for interdependencies among the availability and quality of natural resources and the competition for the resources between different economic sectors, i.e., energy, agriculture, households, industries, etc.

Various models at different scales investigate energy and land use sectors independently from one another without accounting for existing complex interactions and competition for natural resources (e.g., MESSAGE (Messner and Strubegger, 1995), BESOM (Kydes, 1980), TESOM (Kydes, 1980), GLOBIOM (Havlik et al., 2011). Some of the models focus only on local aspects of resource and demand management, others provide aggregate development projections. However, regional, national, international policies can induce serious local changes and, conversely, local changes can have global implications. Therefore, improving our understanding and planning of complex interdependent systems require new models enabling not only global-local interdependencies, but also multiple systems interactions. The model which develops in this report runs at fine resolutions, e.g., coal mines, at the level of counties, prefectures- the resolution depends on the availability of data. At the same time, the model allows for incorporating exogenous projections of coal and crop demand from more aggregate models. In a sense, the model permits spatially detailed analysis of coal and agricultural production expansion consistently with available national, sub-national, regional trends estimated by global models, i.e., MESSAGE, GLOBIOM. Let us point out this version of the model is deterministic but it can also be extended to a dynamic stochastic version in order to explicitly account for uncertainties and risks inherent to energy and agricultural sectors. The model investigates local impacts of "projected" aggregate demands by including local resource constraints; land suitability, environmental and social conditions as it is discussed in section 2. In section 3, a case study in Shanxi province focuses on possible consequences arising from the competition between the coal and agricultural sectors for scarce water resources. Shanxi province has been selected as a representative example of a serious mismatch between the high demand for and scarce availability of water. In a rather general way, section 3 uses scenario analysis investigating limits of the coal industry expansion in Shanxi. Section 4 provides concluding remarks.

2. Modeling framework

2.1 Motivations for the development of the systemic model

The Chinese government has recognized the problem of water scarcity. In December 2013, the guidelines from China's Ministry of Water Resource called "water allocation plan for the development of coal bases", suggest to plan the coal expansion accounting for the balance between water demand and resources on the sites. Planning and implementation of feasible measures in coal-based industry directed towards improving sustainable use of natural resources requires systems analysis approach to avoid potential negative effects of the inconsistent measures. In the following we present the basic version of the model that can be easily extended and adjusted to various situations. In this paper, in order to simplify the discussion, we avoid explicit treatment of inherent uncertainties and non-linear security (performance) indicators.

2.2 Outline of the model

The model has a rather general character and can be applied to investigate development prospects of multiple interdependent systems under restrictions on natural resource use. In this work we present its pilot version focusing on the coal industry and investigating its competition with agricultural production for water and land resources in China. With a help of a scenario analysis the model evaluates resource, economic, and technical feasibility of plausible coal and agricultural demand trends in the presence of (energy, food, environmental) security goals and uncertainty about natural resources. Water and land act as limiting factors for the allocation of new and expansion of existing coal-related infrastructure.

We divide the coal-based industry into three stages: coal mining, processing and conversion. In our model a decision-maker minimizes the cost of the whole cycle of coal production from mining to processing, transportation and conversion, as well as the cost of producing agricultural commodities. Trading can be considered a conversion process.

Environmental considerations play an essential role in the choice of technologies. Seeking for lower cost under tight constraints on emissions and resource availability causes introduction of new and retrofitting of old coal mining, processing, and conversion technologies. The choice of different coal-related technologies depends on region-specific resource and demand constraints. For example, in a rich coal location, water scarcity can prevent implementation of the wet washing technology. In this case, the model evaluates the trade-off between the cost of dry washing, the cost of transportation and wet washing, and the no washing technology. In the latter case, the coal efficiency at the conversion stage will be lower while the emission of harmful pollutants will be higher. So the central planner in her attempt to optimize the costs under the resource constraints takes advantage of spatial planning.
The structure of the model is presented in Fig.2. In the next section we proceed with the mathematical description of the model.

2.3 Indices

The model accounts for various coal mining, processing and conversion technologies, as well as for different types of crops in a number of locations within the region under investigation. We consider the existing technologies as well as those, which are only at the beginning of implementation or even in the research stage, for example, various carbon capturing technologies. Index *i* is used to denote the type of coal, which is a combination of the coal class, the extraction (underground room-and pillar or long wall mining, surface strip or auger mining, etc.) and the processing (washing, cleaning, purification, enrichment) technologies, for example, lignite class, longwall mining, and wet washing. By *t* we denote a coal conversion technology resulting in end-use product (electricity, coke, heat, gasification and liquefaction). Import and export can also be considered as a way of conversion. Index *k* is used to represent different types of crops (corn, wheat, soybean etc.). Indexes *j* and *m* are used to denote different locations within the case study region. Depending on the chosen resolution, it refers to a county, a city, or a smaller geographical unit. Index *d* defines the end-use product such as electricity, gas, oil, coke, etc.

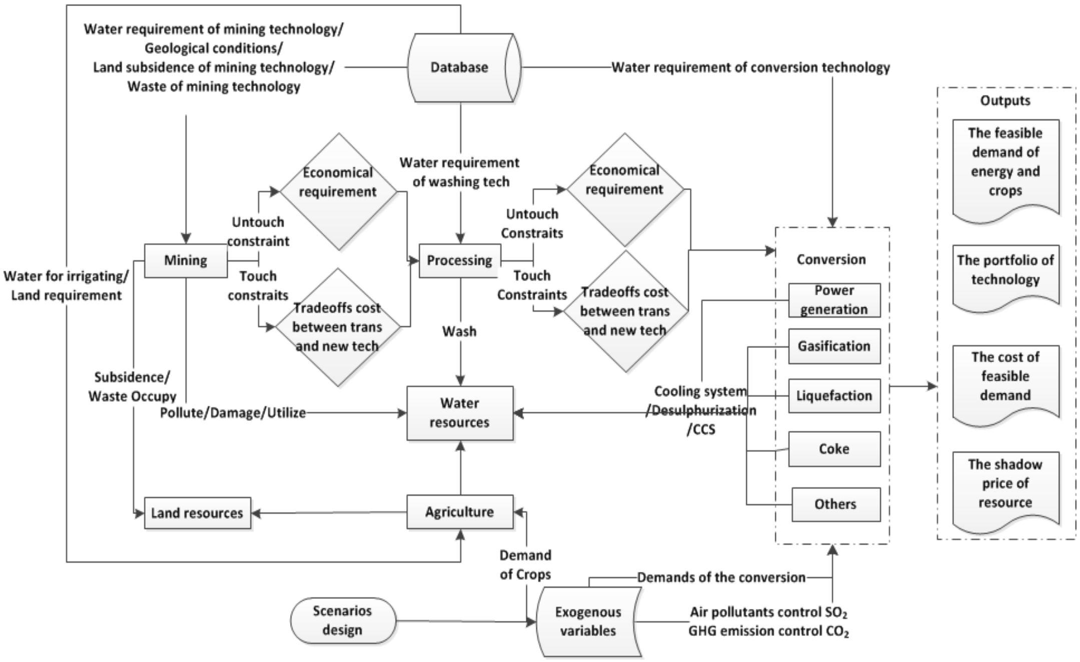

Fig.2: The structure of the model

2.4 Main Variables and goal function

In the model, variables x_{ijmt} denote the amount of coal (in tons) of type *i* produced in location *j*, transported to location *m* and utilized by technology *t*. Variables y_{kjm} denote the amount of crop (in tons) *k* produced in location *j* and exported to location *m*. A social planner chooses how much of coal *i* and agricultural commodities *k* to produce in location *l*, so that the total cost of coal and agricultural production, transportation, convertion is minimized and constraints on natural resource utilization, environmnetal pollution, food security, energy (coal end-product) demand are fulfilled. The goal function is formulated as follows:

$$\min_{x,y} \sum_{i,j,k,m,t} \left[c_{ij}^{CP} x_{ijmt} + c_{ijm}^{CT} x_{ijmt} d_{jm} + c_{ijt}^{CC} x_{ilmt} + c_{kj}^{AP} y_{kjm} + c_{kjl}^{AT} y_{kjm} d_{jm} \right] \tag{1}$$

where c_{ij}^{CP} stands for the production cost of a unit (ton) of coal of type i in location j, c_{ijm}^{CT} stands for the transportation cost of a unit of coal i from location j to location m, c_{ijt}^{CC} defines the conversion costs of a unit of coal i by technology t in location j, c_{kj}^{AP} are costs associated with production of a unit (ton) agricultural commodity k in location j, c_{kjm}^{AT} stands for the transportation cost of a unit of the agricultural commodity k from location j to location m, d_{jm} stands for distance(km) between location j and m By x and y we mean the sets of all x_{ijmt} and y_{kjm} correspondingly.

2.5 Resource and security constraints

2.5.1 Land constraints

As mentioned in the introduction, in China about 40% of the total farmland area overlaps with coal reserves. The model incorporates two main farmland disturbances from coal mining - land subsidence and gangue (waste) deposits, both lead to land loss. A number of researches have done prediction of the land subsidence rate due to coal mining (Reddish and Whittaker, 2012; Donnelly et al., 2001; Xu et al., 2014). The character of the subsidence depends on the disposition of mined strata and also on the mining process in place (Chadwick et al., 1987). For example, if backfill mining is applied, the land subsidence can be prevented or controlled as voids are filled in with the low-cost solid materials, coming, e.g., from tailings. Using gangue for filling in the voids helps decrease the area occupied with the waste deposits. Subsided land can be recovered by reclamation programs; however it can take long time (Cong, 2013). Therefore, in our model we divide the farmland into three types: the land used for agriculture, subsided land and the land occupied by the gangue. We impose a land constraint prescribing that the total land used for agriculture, the land which subsides due to coal mining and the land occupied with waste deposits cannot exceed the total farmland in each location. Thus, the constraint is formulated as follows:

$$\sum_{k,m} l_{kj}^{A} y_{kjm} + \sum_{i,m,t} x_{ijmt} (1 - r_{ij}) \Delta l_j l_{ij}^{S} + g \sum_{i,m,t} x_{ijmt} \le L_j , \tag{2}$$

where l_{kj}^{A} stands for the area of farmland required for production of a unit of crop k in location j, l_{ij}^{S} is the area of land that subsides as a result of coal mining of a unit of coal of type i in location j, Δl_j denotes the fraction of the farmland overlapped with the coal filed in the location j, r_{ij} stands for the land reclamation rate (or efficiency rate) for coal i in location j. Coefficient g stands for the coefficient of the gangue[1] occupied area resulting from the production of a unit of coal i in location j (see Appendix for the details on the calculation of g).

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[1] Gangue is left as a result of separating coal from other materials. It is important to separate gangue from lump coal before fed to thermal power plants.

2.5.2 Food security constraints

We assume that the region under investigation aims to produce enough food to provide a required amount of calories (nutrition norms) to its population, i.e., ensure food security. Domestic production can be supplemented by imports, however at higher costs. Thus we impose a constraint on the minimal required level of commodity k in location m as follows

$$\sum_{j} y_{kjm} \geq D_{km}^{A} \tag{3}$$

where the right-hand side D_{km}^{A} defines the demand for agricultural commodity k in location m. This constraint requires accounting for transportation costs in the goal function (1) among locations having shortages and overproduction. Note that D_{km}^{A} can be measured in terms of the minimum amount of daily calories per capita suggested by the World Health Organization (WHO) accounting for the size, age, sex, physical activity, climate, and other factors (Anderson, 2014).

2.5.3 Energy security constraints

Our model is driven by an exogenous demand for the final energy (electricity) converted from coal. Apart from electricity, the model includes the demand for such end-products of coal as heat, coke, gas, and oil. The demand scenarios at national or subnational levels can come from aggregate models. The conversion efficiency depends on the conversion technologies. Energy security constraint is responsible for fulfilling the demand for the end-products from coal. It is introduced as follows:

$$\sum_{m,t} \alpha_{ijt}^{d} x_{ijmt} \geq D_{j}^{d} \tag{4}$$

where α_{ijt}^{d} denotes conversion efficiency of coal type i in location j by technology t, end-products are denoted by d, and D_{j}^{d} defines the demand for end-use product d.

2.5.4 Water security constraints

Since water plays a key role in coal production and at the same time it is essential for agriculture and for the daily use of regional residents, we impose a constraint on total water consumed for coal extraction, processing and conversion as well as for crops irrigation in each location j:

$$\sum_{i,m,t} w_{ij}^{P} x_{imlt} + \sum_{i,m,t} w_{ij}^{d} x_{ijmt} + \sum_{k,m} w_{kj}^{c} y_{kmj} \leq W_{j} \tag{5}$$

where w_{ij}^{P} defines the amount of water required to produce a unit of coal i in location j, w_{ij}^{d} is the amount of water required to convert a unite of coal i in location j, w_{km}^{c} is the amount of water required to irrigate a unit of crop k in location j, and W_{j} defines water availability in location j. Note that constraints on water use can be introduced in the model separately for coal production (mining) and coal conversion.

2.5.5 Environmental security

The environmental security considerations are introduced in the form of emissions constraints, in particular, on emissions from coal conversion, of which SO_2 and CO_2 are the most important ones (Kreucher et al., 1998). In the model we include technologies, which are able to reduce SO_2 and CO_2 emissions, however, at a cost of additional water consumption.

SO_2 is generated during the combustion of coal. The coal-based power plants are the main source of SO_2 emission in China (Xu et al., 2012). In the future, due to the air emission standards to come into force, both new and existing coal-based plants will be required to install a Flue Gas Desulfurization (FGD) system in China. A wide range of commercial FGD processes are available to remove SO_2 from the flue gas. By far, wet scrubbing system is the most common one with 80% of the global installed capacity. However the FGD systems require a lot of water and their introduction will increase water needs for coal-based power plants too (Carpenter, 2014). Thus, we impose a SO_2 emission constraint associated with the coal conversion in location j, which sets up an upper limit for SO_2 to be emitted in the location as follows:

$$\sum_{i,m,t} e_{ijt}^{SO2,d} x_{ijmt} \le E_j^{SO2} \tag{6}$$

where $e_{ijt}^{SO2,d}$ is SO_2 emission rate from coal i in location j by technology t turn into the end-use product d ; E_j^{SO2} defines SO_2 emission cap in location j

Apart from SO_2, coal-based power plants are the largest contributors to the atmospheric CO_2 concentrations. According to the IEA estimates, CO_2 resulting from coal-based power plants accounts for 45% of the total GHG emissions from fossil energy in China (PD, 2012). In order to decrease CO_2, China needs to considerably reduce the coal demand and supplement coal mining with carbon capture and storage (CCS) technologies. The timing and rate of this process will depend on the stringency of the near-term climate policy and will have important implications for the stranding of coal power plant capacity without CCS (Johnson et al., 2014). China will require commercial deployment of the CCS technology to begin in the next few years. The importance of CCS is expected to grow between 2020 and 2030 (WRI, 2010). However the CCS systems require additional cooling involving water. Introduction of the CCS systems, such as the wet cooling tower, doubles the water use at coal-based plants (Zhai and Rubina, 2011). Given that, the water pressure in coal-producing regions in China is expected to become even stronger.

In our model we impose a CO_2 emission constraint associated with coal conversion by setting up an upper limit for CO_2 emissions as follows:

$$\sum_{i,m,t} e_{ijt}^{CO2,d} x_{ijmt} \le E_j^{CO2} \tag{7}$$

where $e_{ijt}^{CO2,d}$ is CO_2 emission rate from conversion of coal i in location j by technology t turn into the end-use product d ; E_j^{CO2} defines CO_2 emission cap in location j

2.5.6 Coal productive capacity

The amount of coal produced in each location is constrained by the coal productive capacity of that location. Coal productive capacity is the maximum amount of coal that can be produced annually depending on geological conditions, mining technology and equipment. According to the Regulation of State Safety Work Administration, for the sake of safety, mining companies are forbidden to produce above the productive capacity which is registered in coal production license (SAWS, 2014). We impose the following constraint

$$\sum_{i,m,t} x_{ijmt} \le C_j^c, \tag{8}$$

where C_j^c stands for the coal productive capacity in location j.

2.5.7. Coal purification and enrichment processes: dry and wet cleaning

Washing coal is a promising way of increasing its efficiency and utilization – it increases the coal quality as well as serves environmental protection. Washing helps remove the waste materials from coal. Also it makes the transportation cost lower. In China, the washing rate of raw coal is relatively low compared with, for example, the one in the USA and Australia. However, recently the Government has acknowledged the importance of washing coal in the energy development 12th Five-year Plan requiring the washing rate to increase up to 65% by 2015. In our model we impose a limit for the washing rate in each location j as follows

$$\sum_{m,t} x_{ojmt} \ge w \sum_{i,m,t} x_{ijmt} \tag{9}$$

where w is the washing rate of raw coal, and index o represents the type of coal without washing.

3. Limits to growth: scenario analysis

3.1 Motivations for the numerical experiments

Numerical experiments are carried out to illustrate that introduction of new and expansion of current coal mining production facilities can be substantially limited by the availability of natural resources. Inappropriate production allocation can lead to dangerous competition for resources among different resource users and increase risks of energy, food, water, environmental insecurity. Our model is designed for the analysis of a wide range of scenarios reflecting resource and energy-food-water-environmental security considerations, e.g., water and land availability, emissions constraints, water quality norms, food security requirements, etc. The model is spatially-detailed. It can be applied at different resolution levels, i.e., national, regional, sub-regional levels. The resolution can be defined by the decision makers' goals while planning project implementation. In what follows, we conduct a case study in Shanxi province. The numerical experiments are designed with a purpose to illustrate that current coal production is already at the limits of available natural resources. Its expansion without accounting for resource limitations and uncertainties can exacerbate the competition between the resource users and worsen sustainable development prospects in the region.

3.2 Case study: Shanxi province

We select Shanxi province as a case-study region for several important reasons. Shanxi is among the six provinces, together with Inner Mongolia, Shaanxi, Gansu, Ningxia, and Hebei, which are planned to uptake 60% of the newly proposed power generating capacities in China (WRI, 2013). These provinces, however, account for only 5% of China's total water resources. So in Shanxi, the competition for water between domestic, agricultural, and industrial users is very serious.

Shanxi is located in the eastern part of Loess Plateau, in arid and semi-arid areas of China. The water environment is fragile because of the topography features and climate conditions. The average annual rainfall level is only about 500 mm, in some areas reaching as low as 200 mm (Dang et al., 2013). Per capita water resource in Shanxi is only 295 m^3, which is equal to 1/7 of the average per capita water resource of China, and to 1/25 of the average per capita water resource in the world (Shanxi Bureau of Statistics, 2014).

Shanxi has high potential for coal mining expansion as it has the richest coal reserve in China, estimated as much as 91 billion tons, accounting for about 40% of the total coal reserve nationwide (NBSC, 2014). Coal-bearing area is about 62000 km^2, which accounts for 40% of the whole province area. Coal is found in 94 (out of 119) counties of Shanxi. In 2012, the total coal production in Shanxi has reached 913 million tons, which is 25% of the total production in China. Of these, 578 million tons are transported to other provinces of China, accounting for 63% of the total production in Shanxi (Shanxi Bureau of Statistics, 2014). According to the Government's 12th Five-year Plan, the annual production of coal in Shanxi should reach 1 billion tons by the end of 2015, 60% of which should go to supply other provinces of China. In 2012, the largest coal production area in Shanxi was Shuozhou producing over 210 million tons coal. Other major coal mining areas, producing over 100 million tons in 2012, are Lvliang, Changzhi, Datong and Jincheng (CCIA, 2013). Some of them, notably Datong, belong to the highest water stress areas in Shanxi province. Even households feel severe shortage of water supply, for example, in Datong the households have not enough water to take showers, what causes serious skin diseases (Chen, 2000).

Because of the water scarcity, agricultural production in Shanxi has never been stable and reliable, mostly because of high frequency of droughts and the lack of complementary measures, e.g., advanced irrigation systems, water retention areas, water supply networks (Hendrischke and Feng, 1999). The irrigated arable land constitutes 29% of the entire farmland; the yield from the rained farmland fully depends on precipitation (Yao and Duan, 2009). That is why, over the time period 1980 – 2010, the average food self-sufficiency of Shanxi was about 67%. In other words, nearly 1/3 of food was imported from other provinces (Yan et al., 2013).

At the same time, the total area of land subsidence caused by coal mining and occupied by the waste of coal mining has reached 68 thousands hectares, of which 40% is the arable land. It is increasing with the rate of about 5 thousands hectare per year, (Qiao, 2007).

Given the recently imposed energy, food, water, environmental security targets, the trade-off between the desire to produce more coal and the need to reduce the risks of not fulfilling food, water, land and environmental norms and constraints in Shanxi province is becoming more profound.

3.3 Data

We calibrate the model using relevant data from 2011 and 2012 years. In the case study, we distinguish 11 major coal and crop production locations corresponding to the prefecture-level cities, i.e. Taiyuan, Datong, Changzhi, Jincheng, Jinzhong, Linfen, Lüliang, Shuozhou, Xinzhou, Yangquan, Yuncheng.

Yields and areas of crops, which are the original data for l_{kj}^{A}, water quantities required by irrigation and industry, which are the original data for W_j, etc., are taken from 2013 Shanxi Statistical Yearbook (see Appendix, Tables 1-3). Data on irrigation water requirements by crops, which are the original data for w_{km}^{c}, (Appendix, Table 7) are compiled from various literature sources (Yang, 2011; Wang, 2011; Hu et al., 2011). Data on coal production in 2012, which are the original data for l_{ij}^{S} and C_j^{c} (Appendix, Table 4) comes from (CCIA, 2012) and areas of coal fields, which are the original data for l_{ij}^{S} – from (Lu et al., 2012). A number of authors provide data on water use by different coal conversion technologies,which is the data of w_{ij}^{d}, (DOE, 2006; Meldrum et al., 2013; Mielke et al., 2010; Macknick et al., 2011; Byers et al., 2014; Pan et al., 2012; Shanxi Provincial Government, 2008). Data on water use by different mining and washing technologies,which is the original data for w_{ij}^{P} (Appendix, Table 6) are summarized from literature. As the distance between any locations we use the transportation radius, which is the original data for d_{jm} (Appendix, Table 8). The conversion efficiencies by technologies, which is the data for α_{ijt}^{d} are provided in (Appendix, Table 9). Coal end-product demand, which is the data for D_j^{d} (coke, electricity, gas, chemicals) (Appendix, Table 10) and crop demand,which is the data for D_{km}^{A} (Appendix, Table 11) are exogenous variables based on actual year 2012 data. The washing rate of raw coal w is 60% which is the goal of 2011.

3.4 Design of experiments

In section 2, the outlined guideline from the government works towards mandatory use of water in an optimal and sustainable way. Numerical experiments pay attention to natural resource distribution, the water consumption by technologies, and the environmental protection in Shanxi. Currently, water resources are allocated to coal and crop production in the form of water use quotas. Expansion of coal production and prioritizing water use for coal over agricultural sector would lead to underproduction of agricultural goods and increase of food security risk. We study the possibility of more efficient redistribution of quotas between the sectors and locations in order to encourage, restrain or prohibit further expansion of coal industries in some locations.

The availability and demand for water depend on many factors, in particular, weather conditions and seasonal precipitation patterns. Shanxi's rainfall is not equally distributed over the year – about 60% rainfall occurs in summers and relatively little in winter and spring with high probability of spring and winter droughts. In general, both, water supply and consumption (demand) are characterized by high variability.

For our numerical experiment we take the water consumption in 2011 as a baseline scenario of water supply. Assume that only supply, i.e., the right hand side of equation (5) can vary around the baselines scenario. Water availability scenarios are explicitly defined for 11 regions and are based on information in Table 3 (see Appendix). We combine water availability scenarios with plausible scenarios of coal and agricultural demand.

In a scenario-by-scenario manner we analyze how slight changes of water availability can affect coal and agricultural production portfolios. We seek to answer a question whether optimal technology sets are robust with respect to water supply scenarios. We show that the model will suggest quite different mix of coal technologies and agricultural crops under different water availability scenarios. Expected, that coal and agricultural demand will increase. However, it is possible that local production decreases due to imports from other provinces or from abroad. In this study we introduce only four water availability scenarios without specifying the likelihood of their occurrence:

a. In business-as-usual (BAU), water availability by regions is based on water consumption data by sectors in 2011 year;
b. High BAU (HBAU) scenario implies 5% higher water availability than in BAU;
c. Low BAU (LBAU) implies 4% lower water availability than in BAU;
d. We introduce also an average water availability scenario (ABAU), which in our experiments is only slightly higher than BAU.

In the HBAU scenario, the water supply is higher; this increase because of, for example, increased rainfall due to climate change in the north of China or due to emerging water retention or conservation capacities. A lower water supply in LBAU can occur because of natural weather variability (e.g. temperature increase, drought) requiring urgent diversion of water for consumption in other sectors, e.g., hydropower or heavy industries. ABAU corresponds to the average water supply across all water scenarios.

Given the current trends, one can expect the coal production in Shanxi to increase in the future. However, it is also very important to explore the lower level of coal production as China will cap coal use by 2020 (Joe, 2014) in order to meet the air pollution targets. In the future, the increase of agricultural production is expected to be driven by growing population and incomes. It is also possible that due to the high coal production agricultural activities in the province will decline. Therefore, in the numerical experiments we assume that coal production can vary from 775 to 1000 million tons, which is within about 10% ranges around the actual year 2011 coal production level of 860 million tons. The range between the largest and the smallest values is divided into 10 equal intervals corresponding to the coal demand scenarios. The demand for agricultural commodities vary from 13.6 to 15.2 million tons (about 5% around the 2011 year production of 14.3 million tons grains), and within this range, 10 alternative agricultural production scenarios are identified. In total, we evaluate 400 scenarios, representing all combinations of coal and agricultural production and water availability alternatives. Water shadow prices are calculated indicating the marginal cost of relaxing or strengthening the water constraint, in other words, how much a policy maker would be ready to invest to increase the water supply.

3.5 Results

3.5.1 Feasible demand set

The model analyzes feasible coal and agricultural production levels and provides optimal mix of production technologies fulfilling energy, food, and environmental security goals under different water supply quotas. Optimal coal and agricultural production for the year 2011 is presented in Fig.3 and Fig.4, respectively. Model-derived optimal allocation is able to account for complex spatial interdependencies among resource availability, demand, and water requirements by technologies; therefore it can be different from the current allocation, which can miss some of the interdependencies. Fig.3 and Fig.4 use sankey diagrams to visualize optimal coal and agricultural production distribution in Shanxi in 2011.

The year 2011 coal demand in Shanxi is 860 million tons; 496 million tons are extracted by long-wall technology and processed by wet washing technology. Among them, 120 million tons are produced in Lvliang. Nearly 652 million tons are exported to other provinces, and the rest is converted into end-demand products by different technologies as it is shown in figure. In the city which is lock of water, the technology set is water saving. For example, in Datong more than 90% of coal is without washing, and transported to the other provinces. As we mentioned in section 3.3, the washing rate of raw coal is 60% in the whole province and no limit in each location, we can see the cities which are lock of water tend to choose “no washing” as the processing technology. As Shanxi is a coal rich province, the energy demand in each city can be satisfied without import. As to minimize the total cost, the coal transport among the cities is unnecessary and nearly 76% of coal transported to the other provinces. Above all, we can see the model can give the spatial technology set suggestion given the constraints.

In Fig.3, Total corn demand in Shanxi equals 14.295 million tons, of which 10 and 3 million tons are corn and wheat demand, respectively. In the model, the demand constraint of crops is the round number of the reality. Therefore, compared with reality which is shown by Fig.5, we can see the optimal location of crops is almost the same.

Fig.6, a-d, displays feasible sets of coal and crop demand under four water supply scenarios. Figure 5, panel (b), shows that in BAU scenario, agricultural production cannot exceed 14.4 mill tons, and coal production is limited to 950 mill tons. The year 2011 coal and agricultural production is marked with “+”. It is within the feasible domain, however lies very close to the domain’s boarder defining maximal feasible agricultural production.

Thus in the BAU scenario, the actual level of coal and crop production is very close to the maximum efficiency frontier. This means that, given the water quotas same as in 2011 year, the planner can increase coal production only very slightly without compromising agricultural production. For example, coal production of about 900-925 mill tons leads to the drop of agricultural production below 2011 level (scenario V1.6 on the horizontal line). On the other hand, reducing coal production will not boom agricultural activities because of the crop land constraints.

Panel (c), LBAU, illustrates that the actual level of coal and crop production would not have been possible to achieve if the water constraint had been by 4% lower.Even if agricultural production were completely eliminated, the coal output of 950 million tons would not be possible.

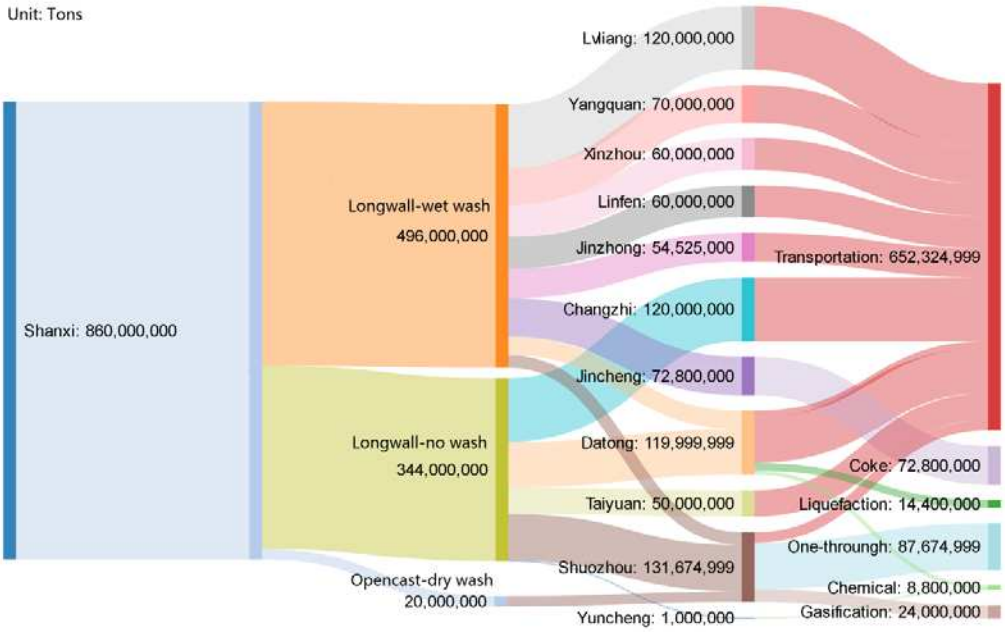

Fig.3: Optimal coal mining technologies and production allocation by regions, Shanxi, BAU water supply, 2011

Panel (a), Figure 5, corresponding to HBAU scenario, shows that a 5% increase of water supply would allow very slight coal and agricultural production increase, i.e., by about 0.15 million tons (1%) for agriculture and 50 million tons (5.26%) for coal.

The horizontal tradeoff lines in Fig.6 are piece-wise linear. Flat segments comprise scenarios, in which the competition for water between the two sectors is not very pronounced. However, scenarios on each of the flat segments can employ different production and water saving technologies.

Let us select point (850, 14.25) as an example, because the "+" in scenarios "c" is infeasible. Tables 1 shows optimal coal technologies – for mining, processing and conversion – calculated with the model under four water supply scenarios in Shuozhou the results show that technologies vary across the water scenarios. In Shouzhou, from HBAU to ABAU, as the water supply decrease, the coal exported to the other province is increase, because exporting needs no water.

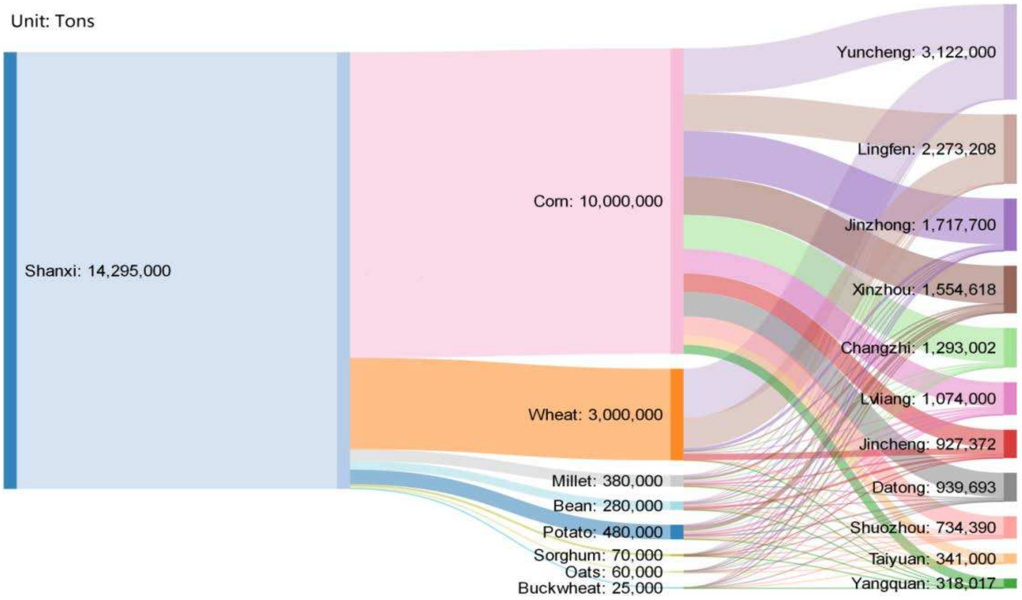

Fig.4: Optimal crop production allocation by regions, Shanxi, BAU, 2011

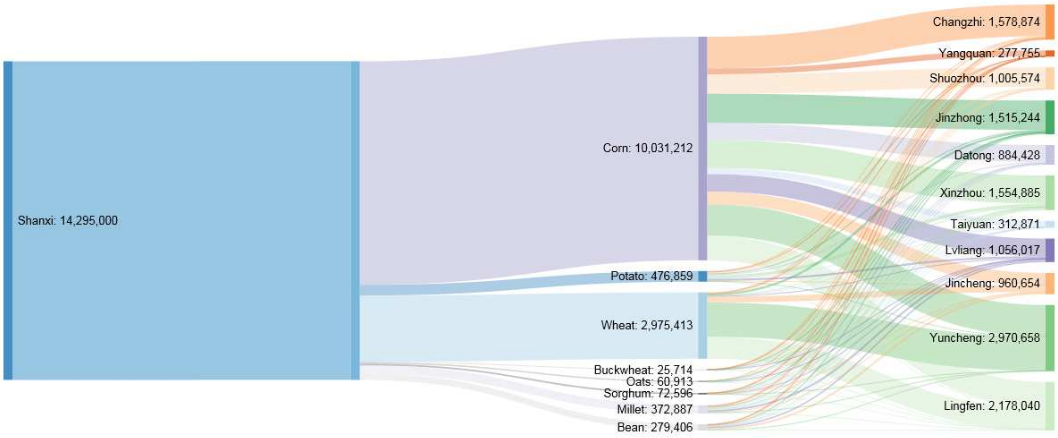

Fig.5: Crop production allocation by regions in 2011, Shanxi

Also the coal without washing increase, because compared with “wet”, both “dry” and “no wash” can save water, however “no wash” is at no cost. In BAU, comparing with HBAU, the coal produced in total is lower; the coal with wet washing decrease, at the same time, the coal for conversion is lower. In LBAU, the amount of coal production keep the same with ABAU, however, most of the coal is without washing and all of them are exported to the other place. Compare with BAU, the water supply in ABAU is just a little bit higher, however, the technology sets are different from each other, what explains the sensitivity of the technological portfolio to rather moderate water supply variations.

As mentioned, decreasing coal production does not lead to a much higher crop output because of the land constraint. The flat vertical tradeoff line indicates that while agricultural production is within the ranges between 13.6 and 14.2 million tons, decreasing the agricultural production would not let coal production to exceed some specified level due to the coal productive capacity constraint (8).

Panel (d) presents the ABAU scenario (only 0.33% higher water availability than in BAU). Traditional technological analysis is often based on average indicators or average values of stochastic parameters such as water availability in our case. Panel (d) shows that the feasible set in ABAU is quite different from the feasible sets corresponding to other water supply scenarios (the feasibility domains have rather different shapes), therefore, relying on average values can mislead policy analysis. Fig.6 confirms high sensitivity of the results to slight water supply variations. Coal and agricultural technologies mix is scenario-dependent, i.e., not robust against water supply scenarios.

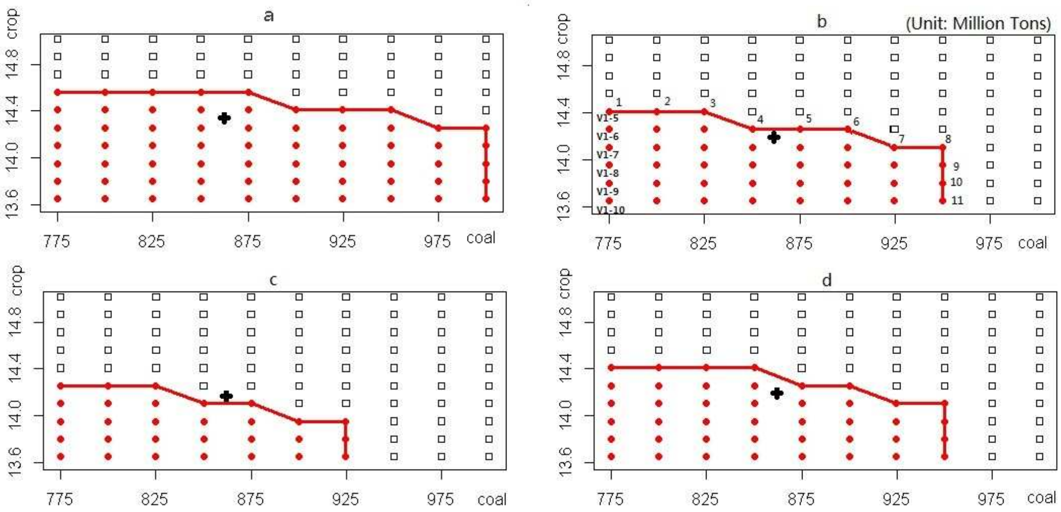

Fig.6: The feasible demand sets for coal and crops under different water constraints. a, b, c, d is on behalf of four different water availability scenarios which we mentioned in section 3.4. X-axis is the alternative demands of crop; Y-axis is the alternative demands of coal. Each scenario has 100 points; each point means one alternative demand combination of crop and coal. The red points are the feasible points under the respective water constraint are marked by red point; the infeasible ones are marked by black squire. Point (860,142.95) marked by "+" is the level in 2011.

Table 1: Coal technologies in Shuozhou under four water scenarios

stages	technologies	Scenarios	HBAU	BAU	LBAU	ABAU
exploitation	underground		200.00	194.47	200.00	193.07
	opencast		20.00	20.00	20.00	20.00
	in total		220.00	214.47	220.00	213.07
processing	wet		27.80	21.17	20.00	20.47
	dry		0.00	0.00	0.00	0.00
	no wash		192.20	193.30	200.00	192.60
	in total		220.00	214.47	200.00	213.07
conversion	electricity	circulation	0.00	0.00	0.00	0.00
		air	0.00	0.00	0.00	0.00
		hybrid	0.00	0.00	0.00	0.00
		one through	0.00	0.00	0.00	0.00
		in total	0.00	0.00	0.00	0.00
	coke		0.00	0.00	0.00	0.00
	gasification		0.00	0.00	0.00	0.00
	chemical		7.80	1.17	0.00	0.47
	liquefaction		0.00	0.00	0.00	0.00

export	212.20	213.30	220.00	212.60
in total	220.00	214.47	220.00	213.07

3.5.2 Water scarcity and shadow price

The model tracks water consumption by coal industry and crop production in each location and permits to identify locations with the highest water requirements and scarcity. Calculating water "shadow prices" makes it possible to analyze how much the water consumption control is needed in each location. In the constrained optimization, the shadow price defines the marginal cost or gain of strengthening or relaxing the resource constraint, respectively. Thus, on the one hand, it reflects the scarcity of the resource and on the other, up to what level a decision maker would be willing to pay for additional resource unit, either from trade or from investing into measures increasing the resource supply (Anni et al., 2003). In order to show how the water shadow price will change with water consumption change in each location we select 6 points where the water consumption decrease as the crop production decrease in the feasible area. Fig.7 displays water prices calculated under BAU water supply and 6 alternative crop production scenarios V1-5 to V1-10 for 11 locations. Scenarios V1-5 to V1-10, Fig.6, imply gradual decrease of crop production, which in some locations causes water price decrease due to the lessening water consumption in agriculture. In the locations without agricultural activities the prices do not change. By ranking the locations according to water prices, the policy makers from the regional perspective can make a feasible energy and crop production plan under the water constraints.

Fig.8 analyzes water use in each location under BAU water supply for 11 coal and crop production scenarios lying on the edge of the feasibility domain as it is shown in Fig.6, panel (b). In these scenarios, the water supply plays a critical role as a factor limiting production expansion (Schoenauer and Michalewicz, 1997). Fig.8 displays how much water is consumed by coal and agricultural sectors in each of the scenarios compared to the total water resource available. For example, in Shuozhou and Datong, the coal and crop production utilizes nearly 90% of the total water resource, which is not acceptable because water is also required in other sectors, e.g., households. Under water scarcity and variability, the required water supply to other water users is not guaranteed. These locations require special water management policies, e.g., construction of water retention capacities to stabilize water supply or water pipe lines to redistribute water quotas between the locations.

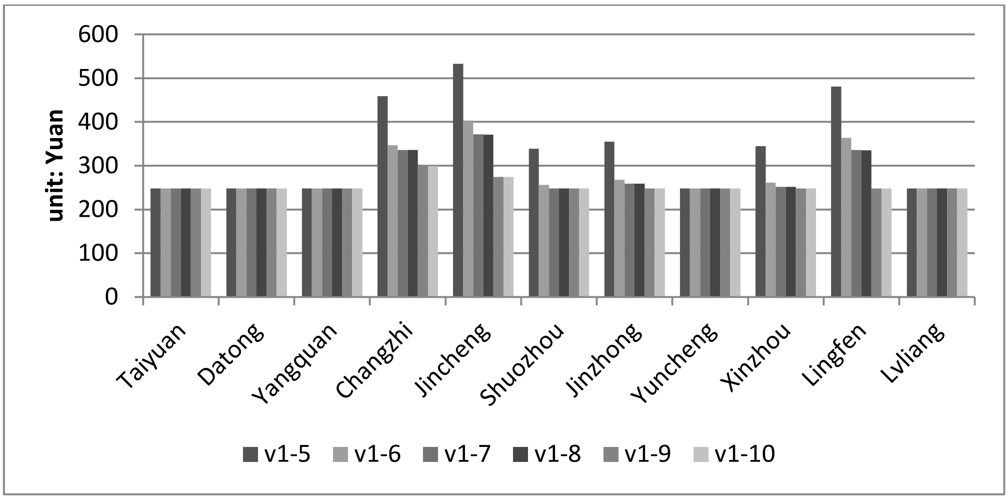

Fig.7: The shadow price of water from different scenarios in each city under the BAU water supply

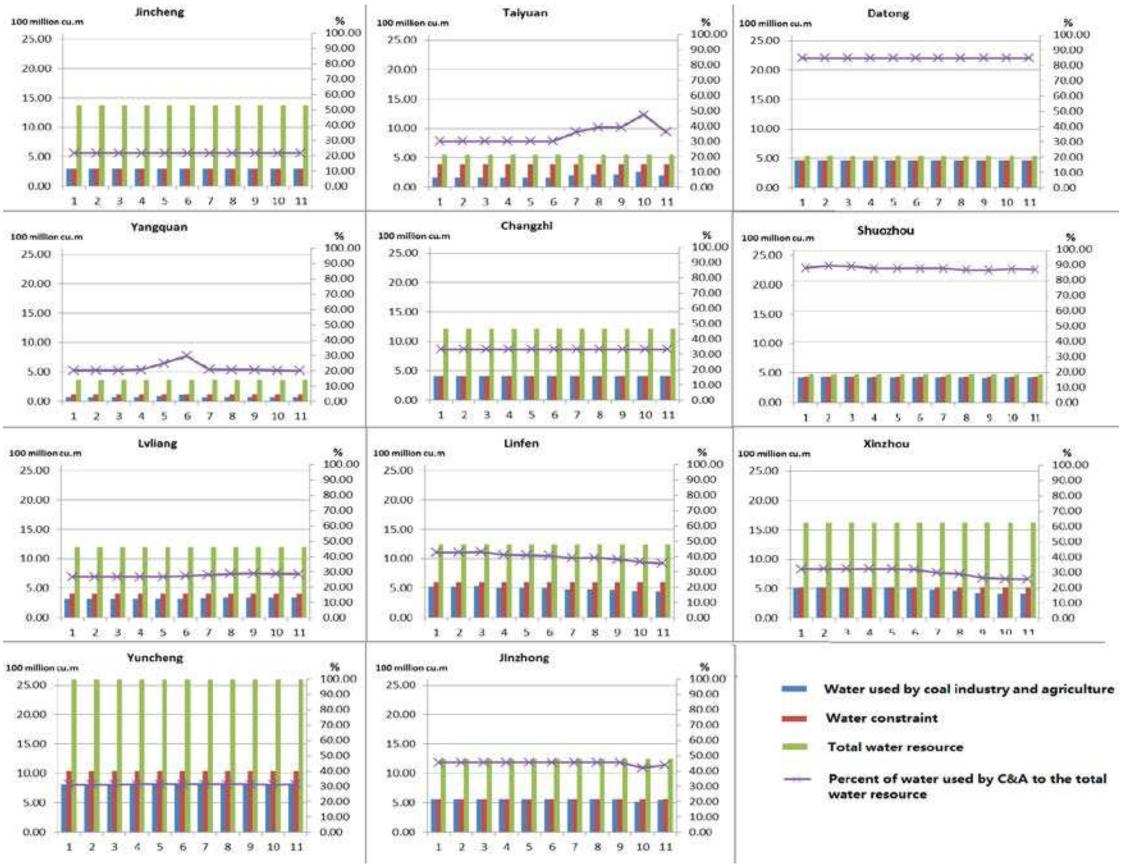

Fig.8: Water consumption by coal industry and agriculture in each location. The red bar represents the water constraint in each location. The green bar represents the total water resource in each location. The purple line represents the percent of water consumption to the total water resource.

4. Conclusions and discussion

The paper emphasizes the importance of accounting for the interactions between the energy, food, environmental security for sustainable developments in China. In particular, inconsistent expansion of coal mining industry in locations with scarce water resources not only increases the energy security risks, but also compromises agricultural production and contributes to food insecurity.

A spatial static model has been developed to support coal industry development in the presence of joint energy-food-water- environmental security goals. The model has been used in Shanxi province for the analysis of the current 2011 coal and crop production structure as well as for the investigation of the planned coal industry expansion in the province. The model-derived optimal production accounts for complex spatial interdependencies among resource availability, coal and crop demand, and water requirements by technologies. Comparing it to the actual production in 2011 allows discovering locations where water scarcity is the limiting factor restricting further coal and agricultural industry developments.

Numerical results in section 3 point out to the risks the coal industry faces if it expands without a systemic analysis of interdependencies between the resource availability and water demand by various users. In fact, the model determines, what technologies and how much of the available resources are actually required to satisfy the coal demand subject to food, land, water, and emissions constraints. For a new coal-based power plant project, the model can help select the optimal location accounting for energy-food-water-environmental security constraints, investments and management options.

Our model also assists in regional water management. Many locations in Shanxi face formidable water management challenges. The model can assist in efficient distribution of limited water resources among water users and locations. For example, the model calculates water shadow prices, which rank locations according to their water shortage risks and set priority for investments into the advancement of water saving, retention, and transfer technologies. Water trading between the locations can also be an important measure to hedge the risks of water scarcity.

Among the main conclusions of the numerical experiments is that under different scenarios of water provision, the model suggests quite different scenario-dependent solutions. For example, Table 1 shows that under different water availability scenarios, the portfolios of coal production technologies are quite different. Practical implementation of such solutions can lead to high adaptation costs if other scenario occurs. It has been also shown that reliance on average values can be seriously misleading. Planning developments under uncertainties requires solutions which are optimal and robust, i.e., in all scenarios regardless of what water availability scenario occurs. As a next step, we extend the model to a stochastic version permitting explicit treatment of uncertainties and robust solutions.

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Appendix

(1) The calculation of “g”

In the processing of coal, gangue comes from two parts of process. The first part comes from mining, which is called extract gangue. In Shanxi, the rate of extract gangue (EGe) is 10%-15% of the coal production. The second part comes from the coal preparation. The rate of this part (EG_p) is 15%-20% of the coal (Liu, 2008). According to the 12th Five-year Plan of coal industry development, the rate of coal preparation (R_P) should achieve 65% at the end of 2015. So we calculate the gangue output, GP_{ijt} in location j from coal of type i and technology t as follows

$$\mathrm{GP}_{ijt} = \sum_m x_{ijmt}(1-R_P)EG_e + x_{ijmt}R_P EG_P$$
$$= \textstyle\sum_m x_{ijmt}(1-65\%)10\% + x_{ijmt}65\% * 15\% = \textstyle\sum_m 0.1325x_{ijmt} \qquad (1)$$

In 2010, the rate of utilization of gangue was 61.4% (Liu et al., 2012), so the gangue which occupy the land (GL) should $\mathrm{A}=(\frac{1}{\mathrm{tanB}\times\mathrm{tanP}}+\frac{3.14}{\tan^2\mathrm{P}})\,\mathrm{H}^2$, where A is the area occupied by the gangue pile, H is the height of the gangue pile, can be calculated by $\mathrm{H}=\sqrt[3]{\frac{6\tan^2\mathrm{P}\times\mathrm{tanB}}{2\mathrm{tanp}+3.14\mathrm{tanB}}} * V$,where- V is the volume of the gangue pile, B is the angle of the waste dump, the value is 16°(Liu et al., 2008), P is the repose angle of the waste dump, the value is 40°, the coefficient of 1.6t / m^3

$$\mathrm{GP}_{ijt}=(\frac{1}{\mathrm{tanB}\times\mathrm{tanP}}+\frac{3.14}{\tan^2\mathrm{P}})(\sqrt[3]{\frac{6\tan^2\mathrm{P}\times\mathrm{tanB}}{2\mathrm{tanp}+3.14\mathrm{tanB}}}\mathrm{GL}_{ijt}/1.6)^2=3.67*10^{-4}(\mathrm{GL}_{ijt})^2. \qquad (2)$$

We assume the weight of every gangue pile is 100t, we can find the coefficient of occupied area from the gangue is 0.0367 which is close to the field data 0.04 in Shanxi (Liu, 2008). At last, we can get the efficient of occupied area from coal is 0.0367*0.1325 ≈0.0049

(2) The data of the case study

Table 1: Sown area of major farm crops in Shanxi (2011) unit: km^2

	Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	bean	Potato
Taiyuan	8.08	554.55	64.08	12.95	6.37	13.32	45.57	70.38
Datong	0.00	1619.06	179.79	20.12	89.25	54.33	124.47	273.59
Yangquan	1.16	478.38	45.46	0.03	0.00	0.05	8.08	18.67
Changzhi	141.74	2044.88	126.88	12.85	2.78	2.68	59.18	103.45
Jincheng	616.80	855.11	76.65	4.01	0.00	0.00	374.43	27.27
Shuozhou	0.73	1446.60	79.82	17.05	140.78	128.48	107.11	328.02
Jinzhong	201.54	2100.52	129.20	31.41	1.03	14.63	182.47	67.94
Yuncheng	3434.01	2758.01	13.95	8.63	0.00	0.00	128.19	3.31
Xinzhou	2.15	2474.74	278.64	17.19	192.75	4.48	242.55	521.40
Lingfen	2357.03	2135.89	163.40	9.37	3.31	7.64	115.89	68.79
Lvliang	71.42	1608.97	382.32	63.35	32.27	13.18	530.53	449.66

Table 2: Output of major farm crops in Shanxi (2011) unit: ton

	Wheat	**Corn**	**Millet**	**Sorghum**	**Oats**	**Buck wheat**	**Bean**	**Potato**
Taiyuan	4649.89	273781.75	9565.38	7184.42	600.15	1709.19	5705.07	9673.61
Datong	0.00	754507.52	35075.48	6277.19	9035.15	6424.54	13899.94	59209.94
Yangqun	614.91	261147.88	9758.72	6.01	0.00	4.00	1470.28	4752.61
Changzhi	51920.49	1423154.36	41091.09	6590.97	208.50	220.01	11856.04	43832.32
Jincheng	271481.47	568508.85	27542.99	1935.76	0.00	0.00	77130.42	14052.57
Shuozhou	424.49	870430.67	19253.99	5300.08	14303.56	12730.90	9970.09	73159.66
Jinzhong	91533.89	1483706.86	35032.44	15213.64	156.10	1449.36	34498.65	21830.41
Yuncheng	1541930.00	1408947.70	3084.43	3386.58	0.00	0.00	11618.80	1690.40
Xinzhou	869.41	1261526.36	71675.70	7253.29	33107.22	615.00	36074.96	143764.48
Lingfen	982160.00	1108235.60	43330.90	2810.90	549.10	889.00	18633.20	21431.40
Lvliang	29828.29	785441.17	77476.36	16637.44	2953.62	1672.19	58548.31	83461.37

Table 3: The water use by irrigation and industry in Shanxi (2011) Unit: 100 million cu.m

	Farmland Irrigation	**Industry**	**water availability**
Total	38.15	14.27	124.34
Taiyuan	1.94	1.98	5.52
Datong	3.24	1.40	5.46
Yangquan	0.34	0.88	3.56
Changzhi	2.43	1.62	12.20
Jincheng	1.08	1.89	13.73
Shuozhou	3.45	0.86	4.76
Jinzhong	4.61	1.06	12.42
Yuncheng	8.75	1.64	26.00
Xinzhou	4.42	0.81	16.26
Linfen	4.95	1.03	12.41
LvLiang	2.94	1.09	12.02

Table 4: The coal production in Shanxi (2011) (C_j^c) Unit: million ton

Taiyuan	**Datong**	**Yangquan**	**Changzhi**	**Jincheng**	**Shuozhou**	**Jinzhong**	**Yuncheng**	**Xinzhou**	**Lingfen**	**Lvliang**
38154200	107186100	54789900	106401900	91261500	187007000	69901000	37330778	48270600	4922	119692100

Table 5: The area of coal field in Shanxi (l_{ij}^S) Unit: km^2

City	Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
Area	1368	632	1484	8500	5350	1603.37	13000	1449.7	4386	15400	10640

Table 6: The water consumption of the technology (w_{ij}^{P})

Mining	m3/ton	processing		m3/ ton	conversion	
long wall	0.25~0.30	wetting clearing	water circuit	0.1	Generic	1.89-4.54(m3 /MWh)
opencast	0.02		dense medium separation		tower-Subcritical	1.49-2.51(m3 /MWh)
backfilling	0.25~0.30*		coal floatation		tower-supercritical	1.73-2.25(m3 /MWh)
underground gasification	0.25~0.30*	dry clearing		0	tower-igcc	1.20-1.66(m3 /MWh)
					tower-subcritical-ccs	3.57(m3 /MWh)
					tower-supercritical-ccs	3.2(m3 /MWh)
					tower-igcc-ccs	1.98-2.11(m3 /MWh)
					one-generic	0.37-1.20(m3 /MWh)
					one-subcritical	0.27-0.52(m3 /MWh)
					one-supercritical	0.24-0.47(m3 /MWh)
					pond-generic	1.14-2.65(m3 /MWh)
					pond-subcritical	2.79-3.04(m3 /MWh)
					pond-supercritical	0.02-0.24(m3 /MWh)
					coke	0.8(m3/t)
					gasification	0.01(m3/m3)
					liquefaction	7(m3/t)
					chemical	8(m3/t)

IGCC: Integrated gasification combined cycle.
CCS: Carbon capture and sequestration.
One: Once through

Table 7: The water consumption of crops in Shanxi(w_{km}^{c}) unit:m3/t

	Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
Wheat	498.06	0.00	541.08	1007.36	838.36	690.99	630.81	638.06	987.66	687.55	1267.87
Corn	394.98	621.22	357.21	226.25	236.90	481.13	276.07	378.78	567.91	372.93	632.98
Millet	1339.88	945.72	931.65	440.01	396.57	764.87	737.61	644.58	717.24	537.36	986.94
Sorghum	726.38	1291.61	1790.37	785.72	834.70	1296.67	832.06	1027.28	954.84	1342.91	1534.55
Oats	5032.38	4682.29	0.00	6320.00	0.00	4665.30	3137.93	0.00	2759.65	2860.14	5178.96
Buckwheat	3506.53	3805.71	5996.25	5489.14	0.00	4541.46	4540.98	0.00	3274.39	3869.60	3546.52
bean	1585.04	1522.29	1088.33	374.37	364.09	1826.35	1047.25	875.57	1142.99	1057.33	1794.17
Potato	151.89	145.55	82.34	63.72	52.39	141.23	64.98	40.89	114.24	67.02	169.71

Table 8: The distance between each place in Shanxi (d_{jm}) unit: km

	Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
Taiyuan	0	272.8	110.8	223	304	207	41.6	383	71	247	182.5
Datong	272.8	0	664	498	580	133.8	304.4	667.4	208.2	527.5	459.5
Yangquan	110.8	664	0	286.6	368.1	305.4	102.2	472.7	173.3	343.4	275.5
Changzhi	223	498	286.6	0	100	437.6	199.7	350.2	305.6	314.9	308.2
Jincheng	304	580	368.1	100	0	520.3	282.3	256.7	388.2	221.4	390.8
Shuozhou	207	133.8	305.4	437.6	520.3	0	239.9	602.9	143.7	473.5	395
Jinzhong	41.6	304.4	102.2	199.7	282.3	239.9	0	386.7	109	257.4	213.3
Yuncheng	383	667.4	472.7	350.2	256.7	602.9	386.7	0	472	143.8	368
Xinzhou	71	208.2	173.3	305.6	388.2	143.7	109	472	0	342.3	265.6
Lingfen	247	527.5	343.4	314.9	221.4	473.5	257.4	143.8	342.3	0	263.1
Lvliang	182.5	459.5	275.5	308.2	390.8	395	213.3	368	265.6	263.1	0

Table 9: The efficiency of conversion technologies (α_{ijt}^{d})

Technology	Value	Unit
one_through	0.33	ton/Mwh
closed	0.35	ton/Mwh
air_cooled	0.36	ton/Mwh
hybrid	0.36	ton/Mwh
gasif	0.00	ton/m3
coke	1.30	ton/ton
liquef	4	ton/ton
chemical	2.00	ton/ton
trans	1.00	ton/ton

Table 10: The demand of the conversion energy (D_j^d)

Energy	Value	Unit
coke	56000000	ton
ele	230173000	Mwh
gas	8000000000	m3
oil	3600000	ton
chem	4400000	ton

Table 11: The demand of the crops (D_{km}^{A}) unit: ton

Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	Bean	Potato
3000000	10000000	380000	70000	60000	25000	280000	480000