Quantitative analysis of natural capital utilization in the provinces along the Silk Road Economic Belt (China section)

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Abstract. The provinces along the Silk Road Economic Belt in China section is undergoing a rapid economic development, but meanwhile poses a severe situation for the ecological environment. In this paper, we involved the pollution discharge account to analyse the pressure of natural capital depletion on the ecological environment from 2005 to 2016 with combination of improved ecological footprint and scissors difference. The results show that: (1) The ecological footprint (EF) in this region almost doubled over the past 12 years, while the ecological capacity (EC) was rather low and experienced a slightly decrease. With increase of ecological deficit (ED), the capital flow could not maintain economic and social development recently, and the depletion of the natural capital stock has become general. (2) Spatially, the variation of EF varies greatly in different provinces, but as a whole, the per capita EF in Northwest region was much higher than that in Southwest. The provinces with high EF depth concentrated in the east and north margin with relatively better economy, while the provinces with high EF size concentrated in northwest region with abundant resources and low population density. (3) The decrease of scissors difference between EF depth and EF size indicates that positive effects of ecological restoration projects have been exerted and the conflict between supply and demand of natural resources tends to be eased to some extent. These findings could provide specific policy implications for this region to improve the efficiency of natural capital utilization and promote the coordinated development of economy and environment.

1. Introduction
The initiative of Silk Road Economic Belt (B&R) proposed by Chinese government in 2013 aims to prompt regional cooperation between China and other countries along the road [1]. While at the same time, as one of the most sensitive area in the world to climatic change [2], it is suffering severe resource and environmental problems, such as soil erosion, land desertification, water resources crisis, and air pollution caused by resources exploitation [3]. Resource constraints and environmental protections has become the biggest obstacle to achieve goals of construction of the “Green Silk Road Economic Belt”. Therefore, in order to promote sustainable development of regional resources and environment, these provinces need to optimize their socioeconomic development model, increase environmental capacity, clarify the utilization of natural capital and improve the utilization efficiency of resources.

Recently, a number of metrics or indicators have been proposed to quantify the natural capital utilization to reflect the degree and level of sustainable development [4]. Ecological Footprint model (EF), as one of the most representative methods for assessment of sustainable development from
ecological perspective, can well deal with the urgent issues these provinces currently faced [5-6]. It offers a comparable indicator by converting annual resource depletion required by the development of socio-economic system as well as absorption of wastes and emissions from this system into the biologically productive area [7-8]. Recently, this method has been widely applied to evaluate the resource and environmental sustainability on global, regional, national or even smaller scales [9-11]. However, previous studies only considered direct CO$_2$ emission in the process of industrial production, but with little attention on various contaminants discharged from domestic sewage, industrial wastewater, solid waste, and soot [12-13]. Correspondingly, footprints of human activities are generally divided into biological resources account and energy consumption account. Such an incomplete evaluation leads to a lack of scientifically mature assessment [14]. Especially in energy-rich regions, the secondary industry with high energy consumption and large waste emission accounts for a relatively high proportion. Moreover, traditional EF model fails to track the stocks and flows utilization of natural capital and to reflect the importance of minimum threshold of natural capital stock consumption for regional ecosystem balance and sustainable development. Therefore, Niccolucci [15] extend the traditional EF model into three dimensions by involving the indexes of footprint depth and footprint size, which can not only horizontally explain whether the utilization of natural resources is overloaded, but also vertically reflect the extent of overload. In order to analyze the usage of natural capital more accurately, Fang [16] established a universal formula to further optimize Niccolucci's 3D EF. To date, it has been widely applied in Hainan Province [17], Shaanxi Province [18], Pearl River Delta Urban Agglomerations [19], Southern Qin Ling piedmont [4], Beijing city [20] and Guiyang city [21], verifying the its effectiveness and reliability.

In summary, although the optimized 3D EF model has been widely used to quantify the utilization of natural capital in previous studies, there are still some specific research questions remained to be further tackled. (1) The ecological footprint accounting is lack of great pressure caused by various pollutants discharged into nature, resulting in an insufficient analysis of regional footprints. (2) As an energy base and an ecological barrier, the research on dynamics of natural capital utilization in provinces along the B&R from spatiotemporal perspective is still insufficient. To solve these questions, in this paper, the pollution discharge account is involved into the EF accounts to synthetically analyse the characteristics on space-time variation of natural capital utilization in this region by using optimized 3D EF method. Then introducing the concept of scissors difference, the overall dynamic relationship of natural capital supply and demand in these provinces would be better revealed.

2. Methods and data sources

2.1. Study area and data sources
The Silk Road Economic Belt in China section (73°26′E–112°04′E, 20°53′N–49°12′N) is located in the central and southwest regions, covering five northwest provinces (Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang) and four southwest provinces (Chongqing, Sichuan, Yunnan, Guangxi) (Figure 1). This region covers a total area of 4,254,500 km$^2$, accounting for 44.32% of the country's land area, with the terrain of high in the west but low in the east. The regional climate is complex and divers, with increased drought degree from south to north and distribution of humid forest, semi-arid grassland and arid desert. The ecological environment is relatively fragile. By the end of 2016, the number of regional population had arrived 320 million, accounting for 23.2% of China. The sum of Provincial Gross Domestic Product in this region reached 1.89 trillion USD, accounting for 17% of Gross Domestic Product of China.

The time series in this paper covers 2005-2016, including specific data of resource depletion and pollutant required. Wherein, biological accounts including the outputs of agricultural products (wheat, corn, rice, beans, cotton, tobacco, oil crop, vegetables, linen, sugar, cocoon, potato, beet, pork), forest products (fruits, bancoul nut, tea, walnut, chestnut, gallnut, palm sheet), grass products (beef, lamb, milk, dairy products, poultry meat and eggs) and aquatic products (freshwater) were collected from Statistical Yearbooks of nine provinces; The energy account (coal, coke, crude oil, gasoline, kerosene,
diesel, liquefied petroleum gas, fuel oil, natural gas, electricity) and pollution discharge account (domestic sewage and industrial wastewater discharge, SO\textsubscript{2} emissions, solid waste accumulation and soot emission) were extracted from China Statistical Yearbook and China energy statistical yearbook. The major indices of pollutant discharge footprint mainly refer to Duan's research [22]. And the equivalence factor and yield factor were obtained from the latest Working Guidebook to the National Footprint Accounts [23] and Yang's research [24].

\[ EF = \sum_{i=1}^{m} \sum_{j=1}^{n} (r_j \times c_i / p_j) \]  
\[ EC = \sum_{j=1}^{m} a_j \times r_j \times y_j \]  

Where \( EF \) and \( EC \) are the total ecological footprint and ecological capacity (ha). \( c_i \) presents the amount of product \( i \) extracted in biological resource account or amount of pollutant \( i \) in the pollution discharge account. \( p_j \) presents the intertemporally average yield for product extraction or the capacity of the land to absorb pollutant emissions. \( r_j \) and \( a_j \) separately present the equivalence factor and the yield factor [23].

In this paper, we adopt Fang’s [16] improved 3D EF method to analyze the natural capital utilization in provinces along the B&R (China section). \( EF_{size,region} \) is defined as the annual occupation area of bio-productive land under the limitation of land capacity, which can represent the scale of natural capital flow utilization. \( EF_{depth,region} \) is defined as the degree of land natural capital depletion exceeded the land capacity [15, 21]. The formulas are as follows:

\[ EF_{depth,region} = 1 + \sum_{j=1}^{m} ED_j / EC = 1 + \sum_{j=1}^{m} \max \left( EF_j - EC_j, 0 \right) / EC \]  
\[ EF_{size,region} = \sum_{j=1}^{m} \min \left( EF_j, EC_j \right) \]  

Where \( EF_{depth,region} \) and \( EF_{size,region} \) are improved EF depth and EF size respectively. \( ED_{region} \) is ecological footprint deficit (ha/cap). \( EF_j, EC_j \) and \( ED_j \) are the EF and EC of \( j \)th land use type separately.
In the improved 3D EF model, the $EF_{depth\_region}$ remains at 1 if the capital flow has been not completely occupied in a certain region. Then we apply occupancy rate of capital flow ($w_{flow}$) to reflect the actual utilization efficiency of capital flow. By contrast, when the capital flow has been completely occupied, the use ratio of land capital stocks to flows ($w_{stock}$) is applied to quantify the range that the capital stock overload [16], following the formulas:

$$w_{flow} = EF_{depth\_region}/EC \times 100\% \quad EF<EC$$

$$w_{stock} = (EF - EF_{size\_region})/EF_{size\_region} = EF_{depth\_region} - 1 \quad EF>EC$$

2.2.2. The scissors difference of EF depth and EF size. Through the calculation of the change rate of the data provided, the dynamics of data can be obtained during a long time series. Here, we introduced the polynomial regression [25] to simulate the dynamic change of $EF_{depth\_region}$ and $EF_{size\_region}$ through its slope of the curve tangent at a given time [26]. The formulas are as follows:

$$y_1 = y_1(t) = EF_{depth\_region}(t) = u_0 + u_1 t + u_2 t^2 + L + u_3 t^3$$

$$y_2 = y_2(t) = EF_{size\_region}(t) = v_0 + v_1 t + v_2 t^2 + L + v_3 t^3$$

(7)

Where variables $y_1$ and $y_2$ respectively represent dependent variables of $EF_{depth\_region}$ and $EF_{size\_region}$. The change rate of $EF_{depth\_region}(t)$ and $EF_{size\_region}(t)$ can be obtained by measuring the derivatives of $y_1(t)$ and $y_2(t)$ shown as the slope of a curve tangent on time $t$. For instance, at the given time of $t=t_0$, if $y_1'(t_0) > 0$, $y_1(t)$ increases with time $t$. If $y_1'(t_0) < 0$, $y_1(t)$ decreases with time $t$. If $y_1'(t_0) = 0$, $y_1(t)$ remains unchanged. The analysis of $y_2(t)$ is same.

The “scissors” was firstly proposed in a report of the 12th Party Congress in 1923 by Trotsky, which represent the blades of industrial and agricultural price levels [27]. Subsequently it was gradually introduced into the field of economic and environmental research. In this paper, the scissors difference was implied to analyze the change trends of $EF_{depth\_region}(t)$ and $EF_{size\_region}(t)$ at the given time ($t=t_0$). The formula is as follows:

$$\alpha = \arccos \left( \frac{1+EF_{depth\_region}'(t) \times EF_{size\_region}'(t)}{\sqrt{[1+(EF_{depth\_region}'(t))^2] \times [1+(EF_{size\_region}'(t))^2]}} \right) \quad 0 \leq \alpha \leq \pi$$

(8)

Where $EF_{depth\_region}'(t)$ and $EF_{size\_region}'(t)$ respectively represent the change rate of regional EF depth and EF size. $\alpha$ represents scissor difference between them. If $\alpha \geq \pi/2$, $EF_{depth\_region}$ indicates a rising trend and changes oppositely with $EF_{size\_region}$; If $0 < \alpha < \pi/2$, $EF_{depth\_region}$ shows a rising trend and changes same with $EF_{size\_region}$; If $\alpha = 0$, no difference showed between the change trends of two indexes; If $-\pi/2 < \alpha < 0$, $EF_{depth\_region}$ indicates a downtrend and changes same with $EF_{size\_region}$.

3. Results and discussion

3.1. Analysis of EF and EC

Figure 2 showed the dynamic changes of per capita EF ($ef$) and per capita EC ($ec$) in nine provinces along the B&R (China Section) from 2005 to 2016. Overall, the regional $ef$ in this region increased from 3.08 ha/cap to 5.07 ha/cap, much higher than the national average (2.53 ha/cap in 2015) [28], while the total $ec$ decreased relatively stable. By 2016, the regional $ef$ was almost 4 times of the $ec$, indicating that the required area has exceeded the available capacity and might lead to overuse of natural capital in this region.
Specifically, the $ef$ in five northwest provinces was higher than that in four southwest provinces. The $ef$ of Qinghai and Ningxia contributed most to the regional $ef$, with both rising nearly 1.5 times to 6.45 ha/cap and 11.16 ha/cap respectively in 2016. While the $ef$ of Guangxi and Sichuan was relatively low, from 1.82 ha/cap and 2.62 ha/cap to 2.19 ha/cap and 3.08 ha/cap with a range of 17.44% and 21.09% respectively. The $ec$ of Ningxia, Sichuan and Gansu increased slightly with a range of 5.55%, 10.61%, and 9.92% separately. While the other provinces all experienced a decreased trend in different extent, among which, the $ec$ of Guangxi decreased most with a range of 8.97%.

In terms of composition of $ef$ in this region (Figure 3), the biological resources accounts of Xinjiang, Sichuan, Yunnan and Guangxi accounted for the largest, which was mainly due to the high yield of characteristic agricultural products and high-quality forest products. In Ningxia and Gansu, energy and grassland footprint made the greatest contribution to the $ef$, which directly drove Ningxia to surpass Xinjiang as the province with highest EF in 2010. In Qinghai, the contribution rates of biological resources account, energy consumption account and pollution discharge account were 27.44%, 52.43% and 20.13% in 2005 and 13.73%, 41.74% and 44.53% in 2016. The pollution footprint replaced energy footprint as major contributor to Qinghai's $ef$. According to the data in Qinghai statistics yearbook, the production of industrial solid waste and household garbage increased from 9.41 million tons in 2005 to 149.5 million tons in 2016, resulting in the $ef$ of solid waste pollution increased greatly. However, it is worth noting that except Qinghai and Xinjiang, the $ef$ of the other provinces has shown a decline trend with various degrees since 2015. Especially for Ningxia, the main reason may be the pollution control and environmental protection measures imposed by the governments, leading to a relatively decrease of the $ef$ and the increase of $ec$.

Figure 2. Dynamics of the $ef$ and $ec$ in the region along B&R (China Section) in 2005 and 2016.

Figure 3. Compositions of the $ef$ in the region along B&R (China Section) in 2005 and 2016.

3.2. Natural capital occupation analysis

3.2.1. Temporal variation of regional EF depth and EF size. The regional EF depth increased from 3.21 to 4.72 (Figure 4), greater than natural length 1, but the EF size increased slightly, only from 0.62 ha/cap to 0.71ha/cap. This indicated that ecological burden continued to increase in the process of economic development and the capital flows could not be able to maintain regional development without the consumption of capital stock. From 2005 to 2008, the EF depth had a volatility growth, while the average EF size basically remained unchanged. And then, the EF depth and EF size showed a similar development trend. In 2008-2010, the EF depth and EF size increased rapidly, by 2011, both of which increased to 4.64 and 0.71 ha/cap. But in 2011-2015, the change rate of EF depth and EF size dropped rapidly and fluctuated around 0, indicating natural capital depletion tended to be steady after a long period of growth.
Except for Xinjiang and Qinghai, the other provinces' scissors difference between EF depth and EF size experienced a decreased trend. As a whole, the scissors difference decreased by almost double from 0.22 to 0.08 (Table 1), indicating that although the use of natural capital stock is still increasing in the provinces along the B&R (China Section), the conflict between the capital stock depletion and the capital flow occupation has eased and the general tendency of ecological environment is well.

### Table 1. Dynamics of natural capital utilization in nine provinces from 2005 to 2016.

| Provinces | EF depth | EF size | Scissors difference | $w_{flow}$ | $w_{stock}$ |
|-----------|----------|---------|---------------------|------------|-------------|
| Shaanxi   | 3.15     | 4.20    | 5.07                | 0.46       | 0.53        |
| Gansu     | 2.27     | 2.59    | 2.73                | 0.42       | 0.51        |
| Qinghai   | 1.60     | 1.78    | 2.81                | 0.82       | 0.91        |
| Ningxia   | 5.20     | 5.60    | 9.52                | 0.67       | 0.83        |
| Xinjiang  | 3.64     | 4.25    | 5.467               | 1.56       | 1.50        |
| Chongqing | 4.12     | 5.49    | 6.43                | 0.33       | 0.33        |
| Sichuan   | 3.01     | 3.11    | 3.23                | 0.39       | 0.42        |
| Yunnan    | 1.87     | 2.17    | 2.23                | 0.51       | 0.59        |
| Guangxi   | 4.00     | 4.63    | 4.96                | 0.45       | 0.45        |
| Region    | 3.20     | 3.98    | 4.72                | 0.62       | 0.67        |

3.2.2. **Spatial difference of EF depth and EF size in nine provinces.** The provinces with high EF depth were located in the east and north margin (Figure 5), especially in Ningxia. The EF depth was 5.19 in 2005, and by 2016, EF depth reached 9.52 (Table 1), meaning that almost 10 times larger than its current area was needed to burden Ningxia's resource depletion. While the value of EF depth in Chongqing, Xinjiang, Guangxi and Shaanxi were in the middle and an area about 5-6 times larger than its current area was required to maintain its resource depletion. Additionally, the EF depth in Sichuan, Gansu, Qinghai and Yunnan were less than 4, shown that stock capital consumption was relatively low, and natural capital could be renewed in 2-4 years. The appropriation of natural capital stocks in these four provinces was better than that in other provinces.

On the contrary, the high value of per capita EF size was mostly concentrated in the middle and western region with abundant resources and low population density, while the low value was concentrated in the southeastern province with relatively dense population and scarce resources (Figure 5). Although Xinjiang's EF size was the largest in nine provinces, it decreased from 1.56 ha/cap to 1.47 ha/cap during the study period (Table 1), that was the same as the change trend of Chongqing's EF size. The other provinces along the B&R (China Section), especially in Gansu, Shaanxi and Qinghai, experienced the increasing trend, with an annual growth rate of 3.88%, 2.74% and 2.55%, separately.
3.2.3. Analysis of \( w_{\text{flow}} \) and \( w_{\text{stock}} \). The \( w_{\text{flow}} \) and \( w_{\text{stock}} \) respectively represent the level of human's actual occupancy of capital flow and sustainable development of a region. Table 1 showed that the high-value provinces of \( w_{\text{flow}} \) were mainly distributed in Xinjiang, Chongqing, Ningxia and Guangxi, all higher than 60%. In Xinjiang, particularly, \( w_{\text{flow}} \) reached 72.62%. While the low-value provinces mainly distributed in Yunnan, Gansu and Qinghai, all lower than 50%. These provinces are characterized with better resource endowment and lower population consumption demand.

In addition, the high-value provinces of \( w_{\text{stock}} \) were located in Ningxia, Chongqing, Xinjiang and Guangxi, among which Ningxia and Chongqing increased from 4.21 and 3.12 in 2005 to 8.52 and 5.43 in 2016, a 2.03-fold and 1.45-fold increase respectively. The consumption of natural capital stocks in these two provinces was nearly 8.5 and 5.5 times as much as the natural capital flows consumption and the sustainability of natural capital utilization was weaker. While the low-value provinces concentrated in Gansu, Qinghai and Yunnan (all lower than 2) and were well below the country's average (2.69) [28], shown that the sustainability of natural capital utilization in these provinces was relatively strong.

4. Conclusions
EF research nowadays has been widely applied to address crucial questions related to sustainable development, including quantification of natural capital depletion and ecological capacity at multiscale regions by measuring the extent of ecological overshoot and tracking the impact of human activities on natural capital. In this paper, the spatial and temporal characteristics of the EF and EC, as well as the natural capital utilization were analyzed to reveal the problems existing in the ecological construction and socioeconomic development in nine provinces along the B&R (China Section).

The results showed that the EF in the region almost doubled over the past 12 years, while the EC was pretty low and experienced a slight decrease, leading to the ecological environment gradually deteriorated, especially in Xinjiang and Qinghai. The ecological pressure in Northwest region was much higher than Southwest. Specifically, the large depletion of fossil energy like coal contributes most to the deterioration of ecological quality, followed by biological resources consumption. While in Qinghai, industrial solid waste and household garbage are the major contributors to the EF.

The capital flow could not be able to maintain socioeconomic development in this region, and an area nearly five times larger than its current area is required to burden its resource depletion now. Spatially, the provinces with high EF depth concentrated in the east and north margin such as Ningxia and Chongqing, and the provinces with high EF size concentrated in middle and western region such as Qinghai and Xinjiang. Temporally, both EF depth and EF size showed increasing trend, while the gap between them was shrinking, indicating that the ecological restoration projects have yielded positive outcomes and the conflict between the capital stock and flow tends to ease.

Funding: This research was funded by the National Natural Science Foundation of China (51874307).

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