# Desertification and its control along the route of China's "Belt and Road Initiative": A critical review

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**Abstract**

The "Belt and Road Initiative" (BRI) was anticipated in 2013 to promote socio-economic development and cooperation across countries in Asia, Europe, Africa and worldwide. Rapid land-use changes and infrastructure developments driven by the BRI program are expected in the coming decades. These anthropogenic effects are likely to exaggerate the process of de-vegetation, deforestation, accelerating desertification, which is one of the major threats to the BRI region. This manuscript studied the desertification facts (i.e. spatiotemporal pattern, impacts and impacting factors) and investigated key aspects for desertification control (i.e. mitigation and evaluation methods) in the BRI countries via an extensive review of literature. We found that desertification has been prevalent in the BRI countries, predominantly in C Asia, but quantitative assessment of desertification is yet fully understood. This review illustrated that desertification was driven by climatic dryness and mis-land-use/management activities, but their relative importance has yet been (quantitatively) assessed along the BRI countries. Given the negative impacts of desertification, these BRI countries have ratified the UN Convention to Combat Desertification (UNCCD) to reduce negative impacts. The implementation of desertification mitigation programmes are currently still lacking. We argued that desertification is usually evaluated via four type of approaches, including quantitative approaches, indirect detection, direct observation and biophysical measurement (e.g. vegetation growth). Future research should be applied by considering the research scope and data availability. Overall, we conclude that BRI countries should carry out transboundary control on desertification. Otherwise, this issue is likely to extend further imminent developments under the foremost BRI program.

### Desertification and its control along the route of China's "*Belt and Road Initiative*": A critical review

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**Data availability statement**

All data are available in the paper.

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**Keywords:** dryland degradation – impacts – causes - mitigation – evaluation – Belt and Road Initiative (BRI)

## 1. Introduction

The "*Belt & Road Initiative* " (BRI) *("一带一路" in Chinese* ), initiated in October 2013 by China (Wang, 2013, Ascensao et al., 2018), is the biggest trans-national program, which accounts for up to 64% of global population and 30% of *Gross Domestic Product*(GDP) across the world (Huang, 2016, Economist, 2016). While infrastructures development (e.g. railway, highway constructions) taking on a leading role (Lechner et al., 2018), the BRI also comprises of inter-connections on dialogues, trades, scientific and technological knowledge exchange, education and talents developments (Huang, 2016, NDRC, 2015). Since the BRI initiated, it has contributed considerably to the cross-country cooperation that was firstly promoted within Asia and then extended to Europe, Africa and other continents (Irshad et al., 2015, Turgel et al., 2017, NRSCC, 2015). This policy encourages the transnational financial and trade cooperation, evidently by founding the "*Asian Infrastructure Investment Bank* " (AIIB) (headquartered in Beijing) (Yu, 2017) and establishing the "*Silk Road Fund* " in the last few years (Fallon, 2015). The BRI program is undoubtedly beneficial for the socio-economic development of Asia Pacific, Central Asia, Middle East, Europe, Africa and worldwide (Ascensao et al., 2018), promoting over a quarter of global trade in the coming decades (Konings, 2018).

Although benefits of the program are expected, uncertainties and challenges associated with the BRI are potentially seen, such as the adverse impacts on ecosystem services, biodiversity and environment (Lechner et al., 2018, Ascensao et al., 2018, Hughes et al., 2020). Most of these areas located within or besides the BRI's Economic Corridors (ECs) (e.g. Central Asia, Middle East, etc.) are categorised as high ecologically sensitive areas (e.g. wetlands, lakes, forest, etc.), which have vibrant ecological species, valuable landscapes and vegetation. Rapid development and investment projects in these ECs may degrade the eco-environment and lead to further exaggerated desertification in drylands and arid regions (Ascensao et al., 2018).

The term '*desertification* ' was firstly used to depict the transfer of productive arable lands in West Africa to deserts in the 1920s (Kertész, 2009). In the 1970s, the "*United Nations Conference on Desertification*" (UNCOD) was organised following the extremely arid/dryness periods from 1950s to 1970s in the region of Sahelian Africa (Kertész, 2009). "*Desertification* " was defined in the conference as, "*Reduction or destruction of the land's biological potential, which eventually results in the initiation and development of desert-like conditions* " (UNCOD, 1977). In the 1990s, the "*UN Convention to Combat Desertification* " (UNCCD) further defined "*Desertification* " as, "*Land degradation in arid, semiarid, and dry sub-humid areas* " (Helldén and Tottrup, 2008, D'Odorico et al., 2013). That is to say, 'Desertification' refers to land degradation in drylands, which generally include "*hyper-arid* ", "arid", "*semi-arid* " and "*dry sub-humid* " areas with precipitation being largely counterbalanced by evapotranspiration (Middleton and Thomas, 1997), excluding hyper-arid areas. Recently, the UNCCD definition of desertification has been challenged as overexploitation of water resources in hyper-arid lands fits well into the concept of desertification, suggesting the necessity for a further expansion of the UNCCD definition to include hyper-arid areas (Martínez-Valderrama et al., 2020).

Drylands support global populations at 38% (Huang et al., 2015), about 90% of which is currently living in the "*Global South* " and "*developing countries* " (D'Odorico et al., 2013). However, these areas are subject to land degradation (Bai et al., 2008), which is mainly driven by desertification (Bayram and Öztürk, 2014). Dryland degradation (i.e. desertification) extensively cost the developing countries at about 4–8% of their GDPs (D'Odorico et al., 2013); further exacerbating local poverty and episodic mass starvation (UNCCD, 2011). This factual impact provided that the Dryland (and specifically the developing countries in Dryland area) is likely subject to an increasing desertification and land degradation according to human-induced and climatic factors (Huang et al., 2015, Huang et al., 2020). However, desertification of dryland area has not attracted as much public and scientific attention as other major environmental issues such as climate change and biodiversity loss (Martínez-Valderrama et al., 2020).

In fact, the BRI is currently covering a large proportion of areas classified as drylands (Figure 1), where desertification is flattering to expand as vegetation (e.g. suburbs, trees and plants, etc.) is difficult to survive (Feng et al., 2015). Desertification has turned into a significant land degradation problem in the geographical regions that have been engaged with the BRI program, particularly in the "*Belt* " terrestrial routes and economic corridors (Dregne, 2002, Dregne and Chou, 1992). For example, in Central Asia (Behnke, 2008, Liu et al., 2004, Jin et al., 2012, Jiang et al., 2019a, Jiang et al., 2019b), North China (Wang et al., 2008, Xu et al., 2019a, Xu et al., 2019b) and Western Asia (Haktanir et al., 2004, EI Shaer, 2015, Darwish et al., 2004, Bayram and Öztürk, 2014, Amin, 2004, Alvi, 1995, Gul et al., 2019).

Natural and human-induced processes are widely acknowledged driving forces for desertification (Feng et al., 2015, Sun et al., 2019), including climatic change, water and wind erosion, over-grazing and excessive farming activities (Dregne and Chou, 1992, Zhang and Huisingh, 2018). For example, climate change may exert adverse effects on the dryland environment (e.g. vegetation growth, hydrological cycle) and eventually lead to a further expansion of the desertified area (Marland et al., 2003, Wang et al., 2004, Zhou et al., 2009, Huang et al., 2015, Zhang et al., 2020a). Mis-land-use/management, such as over-grazing, logging, underground water exploitation, inevitably eliminates vegetation that prevent soil erosion by intensive rainstorms and strong winds, eventually threating regional ecosystems and largely accelerating the desertification (Zhao et al., 2005, Zheng et al., 2006, Zhang et al., 2020b).

Future developments under the BRI program will likely lead to substantial land-use changes and infrastructure constructions, which facilitate further expansion of deforestation, de-vegetation and green spaces shrinkage. These human-induced developments will interfere the dryland environment and spread out the risk of desertification, particularly given the fact that the BRI policies and practices have been executed between East Asia (includes China), Central Asia, West Asia and Eurasia regions (NDRC, 2015, Hughes et al., 2020). The comprehensive desertification control measures are thus required under the BRI program to promote the eco-environmental protection in all countries that joined the program unanimously. These measures should be established; on top of an exhaustive understanding of desertification, such as the potential impacts and driving forces. Evidently, the Chinese Government has recognised to implement the ecological friendly programs that include the "*Ecological Civilization* " program (Lechner et al., 2018). Recently, the Government has further pushed the sustainability practice in the BRI program and established the "*Green Belt Development* " practice (e.g. promoting using green finance, and encouraging green energies) that aims to achieve Low Carbon and Sustainable Development Goals (Liang and Zhang, 2019).

In this paper, we aimed to review and investigate the desertification and its control measures in the BRI countries. Based on extensive review of literature (e.g. journal articles, books, conference papers, reports), we systematically investigated the desertification situation (i.e. spatiotemporal pattern, impacts, impacting factors), and key components for desertification control (i.e. mitigation and evaluation strategies). We provide some solutions and policy recommendations that aim to offer ways to mitigate the desertification in the BRI countries.

## 2. Geographical domain of the BRI region

The BRI program is predominantly focused on the ECs and specific development areas (Lechner et al., 2018, Menhas et al., 2019). On the terrestrial areas, it focuses on building several economic corridors, namely, the "*Eurasian Land Bridge Economic Corridor* " (ELBEC), the "*China-Mongolia-Russia Economic Corridor* " (CMREC), the "*China-Central Asia-West Asia Economic Corridor* " (CCAWAEC) and the "*China-Indochina Peninsula Economic Corridor* " (CIPEC) (Figure 1). At Maritime (coastal) environment, the BRI program concentrates on developing the "*China-Pakistan Economic Corridor* " (CPEC) and the "*Bangladesh-China-India-Myanmar Economic Corridor* " (BCIMEC). The intention of developing the corridors is to promote further development of the BRI through a multi-functional approach (Narain et al., 2020), which is established and combined with international trans-national freight logistics and transport routes, key cities to enhance new developments and infrastructures (i.e. industrial parks) in the BRI region.

Four out of the above six ECs are facing drought threats, including CMREC, CCA-WA-EC, ELBEC and CPEC (NRSCC, 2015) (Figure 1). Some countries located in the dryness regions, such as Kyrgyzstan, Mongolia, Pakistan, and Egypt, are suffering from severe drought effects due to lacking of adequate water resources under the aridness climatic pattern. In addition, these areas are also comparatively sensitive to climatic change and anthropogenic (human-induced) interventions (Huang et al., 2015) (Figure 1). Dryland degradation (i.e. desertification) is currently widespread in the BRI region, which requires more attention put into practice of the BRI program.

**INSERT FIGURE 1 HERE**

## 3. Literature analyses

We understand that the BRI currently is at the early stage, which is still undergoing a global expansion progressing (Hughes et al., 2020), as more countries continue to join the program. In this review, we considered that the potential BRI developments and the resulting impacts are predominantly located across the ECs, given that these regions are mainly composed of developing countries that need urgent economic development and infrastructure construction. In line of this respect, Sixty-six countries were involved in the BRI program that are located among the E and SE Asia, the "*Association of Southeast Asian Nations* " (ASEAN), W Asia, S Asia, C Asia, Russia and surrounding countries and C and E Europe (Figure 1). A bibliographic search of relevant literatures was conducted in June 2020, in prior to analysing the desertification patterns in these countries.

The literature search was conducted via "*Thomson Reuters©* , *Web of Science* , and *Google Scholar* through using the key words "*Desertification* " + "*BRI* " and "*Desertification* " + "*Each of the BRI countries* ". Based on a preliminary search, we found that the number of journal articles about the topic was relatively limited for the BRI region, suggesting that the desertification along the BRI has not received sufficient research attention, a similar situation to desertification research on wider dryland areas (Martínez-Valderrama et al., 2020). In order to obtain as much information as possible for a comprehensive review, we extended the search to include books, grey literature, newspapers and official webpages. As a result, we initially retrieved 185 items. A further check of each of the items was then done and only those directly relevant to desertification and its control in the BRI region were included in this study. Finally, we found 163 items for a further analysis, including journal articles (103), books and book chapters (16), conference papers (20), grey literature (e.g. policy and governmental documents, 19), newspaper (3) and webpages (2) from 1980s to 2020. The searched literature covers studies that are relevant to desertification over the BRI countries.

We found that between the years of 1980 and 2001, the number of literatures related to desertification in the BRI countries remained at low numbers (no more than 3 items per year) (Figure 2). However, between the years of 2001 and 2020, there was an increase in the concerns about desertification, reflected by the amount of publications and research outputs. The number of publications keep on staying at a high level between 2018 and 2020, over which about 10 items were published per year. All the selected literature was carefully checked to collect the information relevant to the aim of our study, the information was summarized into tables (i.e. Tables 1-5) to facilitate an in-depth and unbiased analysis and comparison. Research progress and future research need were then described and discussed.

**INSERT FIGURE 2 HERE**

## 4. Facts and implications (Spatiotemporal pattern and socio-economic changes) of Desertification

### 4.1 Desertification facts

Most of the BRI countries are landlocked countries with large-scale agricultural production (NRSCC, 2017) that exacerbates the degree of desertification. Thus, the desertification is widespread in the BRI region. Nevertheless, some driving factors of desertification (e.g. climate condition and human interventions) are not the same across different BRI countries, which indicate that the desertification situation in different areas have specific characteristics (NRSCC, 2019).

In East-Asian region, China and Mongolia both have been suffering from desertification seriously. Ninety percent of the Mongolian territory is vulnerable to desertification and around eighty percent of the land-use areas have already been desertified (Asigang, 2017), although some land restoration has been implemented in NW and NE Mongolia (Wang et al., 2020). These land-use areas are mainly used and operated as the rangelands (grazing areas) for supporting about $3.0 \times 10^7$ heads of livestock and numerous populations of wild animals. In China, desertification land surface areas expanded dramatically from $1.37 \times 10^5$ km$^2$ to $3.85 \times 10^5$ km$^2$ between 1950s and 2000 (Zhang and Huisingh, 2018), when the desertification was primarily found in steppe areas and the fringe area of deserts (Wang et al., 2002). During the decade of 2000 to 2010, total desertification region in China decreased by $1.37 \times 10^3$ km$^2$(Zhang and Huisingh, 2018, Tao, 2014). Desertification is severely widespread in N China. In the 1980s, the area of desertification-prone land area was about $3.34 \times 10^5$ km$^2$, and about $1.76 \times 10^5$ km$^2$ was desertified (Zhu et al., 1988, Xue, 1996). Recently, desertification and its mitigation were found over a $7.50 \times 10^5$km$^2$ of land in N China, and subject to a heterogeneous spatial pattern (Xu et al., 2019a). During 2011–2030, the desertification risk in N China was found by Xu et al. (2019b) to decrease under RCP4.5 and RCP8.5 scenarios. However, some regions, e.g., Turpan Hami basin and Zhungeer basin, become more sensitive to desertification.

Countries in SE Asia (such as the ASEAN countries) are normally not geographically categorised as arid or semi-arid countries (Figure 1). Even though some regions/countries, such as Vietnam and Thailand, are still at a risk of desertification resulting from prolonged droughts (Anh et al., 2006, Sok et al., 2017, Hien et al., 2019). For example, in Vietnam, forty-five percent of agricultural land has been affected by droughts, and 30% of them have been severely degraded (Hai et al., 2013). Overall, the country has over $9.0 \times 10^4 km^2$ of barren area, covering 28 % of the country's total land area, of which $7.5 \times 10^4 km^2$ has been affected directly by desertification (Yan, 2015, Anh et al., 2006). In Thailand, the Pa Deng sub-district and the Huay Sai district are two of desertification-prone areas. Over 10% of the former was found to be subject to different levels of desertification (low level, moderate level, and high level were 2.0%, 9.1% and 0.8% of the total area, respectively) (Wijitkosum et al., 2013). In the latter, most areas (74.4%) were subject to high desertification risk in 1990s, and the risk was still high (77.2%) in 2010s (Wijitkosum, 2016).

Desertification is also widely distributed in West Asia. Dregne (1992), Mamdouh et al. (1999) assessed the desertification for the "*Middle East and North Africa* " (MENA) region (including countries located in Sahara Desert), through refining Dregne (1992)'s assessment for desertification in irrigated areas ("slightly/not desertified" was changed to "not desertified") and rangelands (the desertified area was adjusted from 80% to 50%). They found that in the MENA region 73% of rain fed croplands and 50% of rangeland were subject to different levels of desertification. In the Arabian Gulf, desertification affected $9.76 \times 10^6 km^2$, representing 68% of the total area in the Gulf, which threatened vastly at about $2.87 \times 10^6 km^2$ area (EI Shaer, 2015). Although the size of threatened or desertified areas varies among countries, Qatar, Bahrain, Kuwait and the UAE are countries mostly suffered by desertification in the region (EI Shaer, 2015).

Desertification in some of the W Asian countries has been previously investigated such as Bahrain, Turkey, Iraq, Oman, Kuwait and Syria. In Bahrain, most of the territory has been found to be at risk of desertification (Thomas and Middleton, 1994), and the aridification is likely to intensify and spread under contemporary climate conditions (Elagib and Abdu, 1997). In Turkey, approximately $3.7 \times 10^5$ km$^2$ are prone to desertification and des-habitation (Haktanir et al., 2004), given that over 60% of the country's territory is located in complete dryness (arid) or half dryness (semi-arid) areas. The desertification is potentially accelerated in the future under the hotter and drier climatic condition that has been projected in Turkey (Bayram and Öztürk, 2014). Across Iran, dryland accounts for over 85% of land area, and desertified and desert lands cover $3.4 \times 10^4$ km$^2$(Pakparvar, 1998). Very severe, severe and moderate desertification account for 12%, 81% and 7% of the desertified area respectively (Sepehr et al., 2007). Besides Iran in the Arabian Gulf, over 92% of Iraq's land area has been subject to desertification (Haktanir et al., 2004), which is particularly prevalent in arable areas (Al-Saidi and Al-Juaiali, 2013). The desertified area has expanded since 1981, particularly since soil, vegetation and eco-environment have been largely damaged by military operations. Down to the gateway (Oman) of the Arabian Gulf, over 95% of surface land area is considered as the "*true desert* " or "*moderately affected by desertification* " (Al-Balooshi and Charabi, 2012). Similar situation also occurred in Kuwait, where very severe desertification prevails, and mean annual desertified land was 285 km$^2$ during middle 1970s-middle 1990s (Al-Awadhi et al., 2003). Desertification caused major constraints on the development in Syria, such as affected Badia Rangelands (Steppe zone), marginal regions, and the agricultural lands, largely limiting the agricultural production (Haktanir et al., 2004).

Whilst, desertification has also been found in S Asia (e.g. Afghanistan, Bangladesh, India, Pakistan, Sri Lanka and Nepal). Most of the climate models projected a dry-season precipitation decline and a monsoon precipitation increase in Southern Asia (Kripalani et al., 2007), which implies higher land desertification risk in the future. We found that around 75% of Afghanistan's area is vulnerable to desertification (Ahmadzai et al., 2008). In India, the total land area suffered by desertification is about $8.15 \times 10^5 km^2$, including $2.62 \times 10^5 km^2$ caused by water erosion, $1.78 \times 10^5$ km$^2$ by wind erosion, $1.76 \times 10^5$ km$^2$ of degradation towards vegetation areas, and $9.47 \times 10^5$ km$^2$of frost shattering (Ajai et al., 2009). Besides, around 90% of Pakistan's territory falls into dryness (arid) and half dryness (semi-arid) climate, and is subject to high or severe desertification risk (Anjum et al., 2010). Thus, out of $7.96\times10^5$km$^2$ of the country's land area, $6.24\times10^5$ km$^2$ are susceptible to desertification, only 4.2% land areas are covered by forests (Hussain and Irfan, 2012). In the NE Himalayan region such as Nepal, around 100 km$^2$ in Dopla and Mustang districts (highlands areas in W Nepal) feature a process of desertification (Paudel et al., 2009).

In C Asia, desertification is one of the major threats to the ecosystem for countries including Kazakhstan, Uzbekistan, Turkmenistan and Tajikistan (Jiang et al., 2019a, Jiang et al., 2019b). In Kazakhstan, over 75 % surface land-use areas suffered from land degradation and desertification; more than 14 % of pastures have been extremely or completely degraded (Issanova et al., 2014). Land degradation and desertification areas are mainly concentrated in ecologically fragile areas, for example in the areas besides the Aral and Caspian Sea and the Lake Balhash (Almaganbetov and Grigoruk, 2008). Sixty percent of the Uzbekistan's territory has experienced different levels of desertification (Behnke, 2008), of which the majority is potentially induced by human activities (Gringof and Mersha, 2006). In Turkmenistan, 66.5 % of the territory has been subject to human-induced desertification (Gringof and Mersha, 2006), and the irrigated land is particularly under an unsatisfactory condition due to salinization (Behnke, 2008). Over 97% of Tajikistan's territory is subject to soil degradation, which mainly occurred in the form of soil erosion (Behnke, 2008). Besides, a modelling work, under the *IPCC RCP 8.5* scenario has found that Middle and N Central Asia and NW China (besides Xinjiang, Inner Mongolia Provinces) are likely to experience an accelerated desertification (Miao et al., 2015).

Across Siberia, the BRI corridors (i.e. ELBEC and CMREC) cover the large areas between the Russia and surrounding countries. Desertification was mainly reported in Russia, Armenia and Georgia around the Black Sea. In Russia, the land-use area that is experiencing desertification reach at $1.25 \times 10^6$ km$^2$ (Kust et al., 2011). In Armenia, about $2.4 \times 10^4$ km$^2$ or 81.9% of the territory is subject to desertification. The severely, strongly, moderately and poorly affected territories cover 26.8% 26.4%, 19.8% 8.8% of the territory respectively (Yerevan, 2002, Susanne Khachatryan, 2013). In Georgia, the south-eastern part of the country is sensitive to desertification, where the catastrophic development of desertification processes begins, as precipitation is less than 200 mm (Davitashvili et al., 2009).

Looking further to Europe, approximately 10% of the total surface land areas are affected by the desertification processes (Rubio et al., 1998). The Mediterranean and Eastern European regions are especially threatened by desertification owing to natural and socio-economic factors (Rubio et al., 1998). We found that 20 European Union (EU) member states declared as countries affected by desertification under the "*United Nation Convention on Combating Desertification* " (UNCCD) in 1992. For examples, EU member states countries located in the C and E Europe; they have been declared and engaged in the UNCCD. In Romania, forty-eight percent of the country's agricultural land ($7.1 \times 10^4$ km$^2$) was affected by drought (Lupu et al., 2010). In S, SE and E Romania, these regions belong to the most severe drought areas during the 2000s (Mateescu et al., 2013). In Cyprus, similarly, some areas prone to desertification is likely to increase from 57% to 70.4% in 2050s under the projection of climate change (ClimateChangePost, 2018). In the C Hungary, the central part of the country is the most sensitive area to desertification because of severe drought and the desertification risk is likely to be enhanced by climate change (Kertész, 2016).

Whilst, most of the BRI countries have declared the development of desertification, the exact desertification area is still only available for 18 (out of the 66) BRI countries in terms of our review (Tables 1 and 2). Given the spatial area and distribution of desertification is crucial for designing and implementing the strategies on controlling desertification, quantitative evaluation of desertification is urgently required for the BRI countries. Moreover, the desertified area for most of these 18 countries was a rough number that is not clearly associated with a specific period (Table 1). That implies that the area of desertified land for these countries was evaluated at a low accuracy and not regularly updated, limiting the analysis of active changes in desertified land areas. The mechanism of monitoring on the level of desertification, and understanding the spatial size of desertification (measured by surface area that suffers from desertification) are therefore essential for the BRI countries in terms of investigating the causes and solutions of desertification. That also addresses some important issues, such as validation of large-scale modelling results for desertification, future development on desertification control; and improvement of sustainable land use planning in half dryness and dryness regions (Zhang and Huisingh, 2018).

In the context of lacking monitoring and quantitative assessment, long-term historical changes of desertification have only been investigated in China, Myanmar, Kazakhstan, and Kuwait (Table 2). Meanwhile, future climate projections have recently been undertaken for some countries in W Asia (Cyprus and Turkey) and C and E Europe (Hungary), S Asia and C Asia. The above analyses of historical changes indicated an enhanced desertification in Myanmar, Kazakhstan and Kuwait, while climate projections have revealed that future climate in S Asia, C Asia and parts of W Asian; and C and E Europe would facilitate the development of desertification (Table 2). Countries that suffered from desertification issues are trying their efforts on controlling and mitigating the effects, with positive results occurring in China that has been witnessed to reduce the level of severity on desertification during the last few decades (Zhang and Huisingh, 2018, Feng et al., 2019). In particular, after 2000s, this reflects if the government implements the land-use conservation, land-use restriction, green space, and forest and vegetation conservation schemes.

**INSERT TABLE 1 and 2 HERE**

### 4.2 Desertification impacts

Desertification leads to a series of socio-economic and eco-environmental issues (Bangladesh and IUCN, 2005), including lowered land productivity (Tao, 2014), reduction of soil carbon storage (Anjum et al., 2010), texture destruction (Zhang and Huisingh, 2018) and economic loss (Cheng et al., 2018). Studies have primarily foci on the influence of desertification on economic development, land productivity and regional climate condition.

In the BRI region, economic cost for desertification is large particularly when taking account of the expense for rehabilitation/desertification mitigation. In the MENA region, the annual average income loss by desertification reached at $1.98 billion. The estimated costs for rehabilitation reached $8 billion per year, which means it costs about $160 billion anti-desertification measures in the region (without considering inflation and other economic factors) for two decades (from 1970s to 1990s) (Mamdouh, 1999). Al-Saidi and AI-Juaiali (2013) found that the cost of combating desertification is around $10.3 billion (USD) to $20.5 billion (USD) in Iraq. This huge cost affects the present and future economic developments and slows down further development. Soil degradation costs around 12% of the country's overall agronomic outputs or account for 2.5% of the *"Gross National Product"* (GNP) in Syria (Haktanir et al., 2004). In China, Cheng et al. (2018) found that desertification costs at the range of 0.6% - 1.1% in the GDP through refining previous estimations. Overall, the economic cost due to desertification is lacking of consideration and assessment in the BRI countries. Even in countries experienced for desertification research (e.g. China), the economic cost of desertification has not been fully evaluated (Cheng et al., 2018).

Desertification also leads to loss of productive lands. For example in Iraq, desertification has many negative impacts and particularly leads to the degradation of productive land-use areas (Haktanir et al., 2004). Looking up north in C Asia, land degradation has decreased productivity by 30% to 40% that occurs in the highland areas of Kyrgyzstan, and decreased by 40% to 60% in Tajikistan (Gringof and Mersha, 2006). Kazakhstan's arable land has lost up to 20% to 30% of its humus (the top soil with soil organic matter and essential for vegetation), and approximately 30% of the pastureland vegetation ($6.5\times10^5$ km$^2$) has been degraded, which largely affected the agricultural developments (Gringof and Mersha, 2006).

Desertification may affect the regional environment. The GCM modelling work conducted by Xue (1996) suggested that the desertification expanded in grasslands of Inner Mongolia and Mongolia largely affected the simulated climate through altering the water balance and surface energy balance. Wang et al. (2020) also found that desertification reversion would alter soil greenhouse gas emission in the eastern Hobg desert, China. More prominently, further land-use changes and landscape deterioration (i.e. deforestation, de-vegetation etc.) caused by rapid developments on infrastructures (e.g. building roads, transport networks, urbanisations, etc.) will exert more adverse impacts of desertification to semi-arid and arid areas and countries that are currently involved in the BRI program. For example, the effects of BRI developments may further exacerbate the dust/sand storms in the dryness and half dryness areas of C Asia and thus enhance the cumulative effects of desertification on local eco-environment and socio-economy (Indoitu et al., 2012).



### 4.3 Impacting factors and their relative importance

Desertification results from numerous natural and anthropogenic (human-induced) factors (EI Shaer, 2015, Feng et al., 2015, Park et al., 2018); and their interactions (Zhang et al., 2020b). Our review provided the specific drivers of desertification that have previously been investigated for 23 countries that recently joined the BRI program (Table 3).

**INSERT TABLE 3 HERE**

In this review, we illustrate the natural and anthropogenic factors that affect desertification are the parched climatic condition and mis- land-use planning respectively. The dominant factors have been assessed for six countries, including China, Kuwait, Turkey, United Arab Emirates, Sri Lanka and Pakistan. In five out of these six countries (i.e. China, Kuwait, Turkey, Sri Lanka, Pakistan), desertification was thought to be principally triggered and accelerated by anthropogenic factors that included unsustainable land use, population growth, and socio-economic development. Whilst, desertification in the United Arab Emirates was primarily triggered by the natural factor (i.e. wind erosion). Anthropogenic (human-induced) activities taking up a crucial role of desertification in the BRI countries, while natural factors become dominated in some dryness and half dryness regions. Still, the dominance of natural and anthropogenic factors has yet been assessed in many BRI countries.

In addition, previous studies on desertification focused on investigating the impact of natural factors (e.g. climate change, temperature, wind pattern, etc.) or solely focusing on anthropogenic factors (e.g. land-use changes, human-induced de-vegetation, new developments, etc.). Few studies have simultaneously addressed the combined factors on natural and human activities and their interactions (Feng et al., 2015, Xu et al., 2019a). Relative contribution on the combined effect by natural (i.e. climatic change) and anthropogenic factors influencing desertification is still vague across the BRI countries. This constrains on the perception and understanding of current fundamental mechanisms of desertification processes; and thus limits the capacity of predicting future desertification pattern.

Furthermore, this also influences the development of an assessment system for desertification accordingly, such as establishing applicable criteria and parameters of control measures (e.g. surface area and expansion of desertification, drought, vegetation coverage, rainfall, etc.). That leads to the misunderstanding of desertification status by flawed perception and mis-interpretation on desertification, and eventually causing the development and implementation of ineffective desertification control measures and strategies (Wang et al., 2008). Recently, Feng et al. (2015) developed the quantitative approach that illustrated "*a pooled regression model* " to estimate the combined effect from natural (climate change) and anthropogenic (human-induced) factors on desertification in China between 1983 and 2012, while Xu et al. (2019) assessed the relative role of climate change and human activities in desertification of North China between 1981 and 2010. Feng et al. (2015) found that actually the human-induced (i.e. socio-economic) factor is the most influential driver for desertification, accounting for 79.3% among all factors and drivers, while Xu et al. (2019a) demonstrated that the climate change (12.6%) was more important than human interventions (7.2%) in desertification expansion. The difference in the findings of the above two research could be attributed to the difference in the geographical domain of their study areas (i.e. the whole of China VS North China). However, similar studies should be encouraged to be promoted further in nearly future that will improve the understanding about the factors and control of desertification over wider areas of the BRI region.

## 5. Desertification mitigation and evaluation - the way forward

### 5.1 Desertification mitigation

The UNCCD is an important platform for desertification control. Whilst, the National Action Plans (NAPs) are crucial for the operation. Almost all the BRI countries have signed the UNCCD and worked out the NAPs. For example, Iran has established a National plan to control desertification in 2004 that heavily emphasise and promote the community participation (Amiraslani and Dragovich, 2011). In 2002, China enacted the "*Law of Combating Desertification* ", and afterwards in 2005, enacted the "*National Plan for Combating Desertification* " (Wang et al., 2013). However, many BRI countries are currently still lacking actual desertification mitigation/conservation programmes, although they have ratified the UNCCD and worked out the NAPs. Several countries that includes China, Mongolia, Myanmar, Pakistan and Hungary have launched a series of key desertification mitigation programmes (Table 4). For example, the " *Three-North Shelterbelt* " project (Li et al., 2012), the project is particularly looking after the source and treatment of sandstorms across NW, N and NE China (Zeng et al., 2014). Other projects in China for desertificatoin mitigation inlcude the "*Grain-for-Green project* " (1999-present), Beijing and Tianjin's "*Sandstorm Sucre Treatment Project* " (2001-2010), "*Returning Farmlands to Forest Project* " (2003-present), "*Returning Grazing Land to Grassland project* " (2003-present) (Feng et al., 2005). Some projects have remarkably benefited regional eco-environment (Table 4). For example, during the implementation of the " *Three-North Shelterbelt Project* ", China has also revegetated a huge land area of 2.2 $\times 10^5$ km$^2$ of forests and restored 8.9 $\times 10^4$ km$^2$ of grasslands (Zhang and Huisingh, 2018).

**INSERT TABLE 4 HERE**

The impact/benefit for most of the mitigation programmes has not yet been evaluated, limiting further improvement of the programmes. Besides, current mitigation measures (of desertification) are still facing up-hill challenges. That includes the tough questions of how to concurrently take account of existing desertification control and potential future problems relevant to global Climate Change that is likely to result in exacerbated aridification, thus depleted groundwater supplies (Amiraslani and Dragovich, 2011, Park et al., 2018, Reynolds et al., 2007, Hughes et al., 2020). Additionally, it should be aware that desertification processes are complicated, any single methods or single approaches may be insufficient for desertification control, and a comprehensive and long-term rehabilitation system should be encouraged to implement, legislate, enact and enforce (Zhang and Huisingh, 2018). The BRI countries should carry out in-depth collaborations to combat desertification.

In fact, a trans-national or cross-boundary cooperation framework established among the BRI countries to control desertification on 10 September 2017. The framework established on the sidelines of the thirteenth session of the *"Conference of the Parties* " (COP13) to the " *United Nations Convention to Combat Desertification* " (UNCCD). That aims to help members cooperate on financing, information sharing, training, and learn from each other via example projects (Xinhua News Agency, 2017). Desertification has been largely mitigated and controlled in large-spatial geographical areas via the implementation of multiple large-scaled initiatives and Regional Programs in China (Zhang and Huisingh, 2018; Wang et al., 2013; Tao, 2014). These successful experiences are obliging to control desertification for the BRI regions (Zhang and Huisingh, 2018, Feng et al., 2019, You et al., 2019, Lyu et al., 2020). Here, we encourage China and all BRI-involved countries (located in dryness areas) to take this opportunity and further collaborate closely with the UNCCD, in prior to implement future cross-boundary transnational policies and practices combating drought impacts, improving water resource management, and halting deforestation; to mitigate and prevent further desertification.

### 5.2 Desertification evaluation

In the BRI countries, methods employed for desertification evaluation include quantitative research approaches (e.g. via mathematical models) (e.g. Sepehr et al., 2007, Zehtabian et al., 2005, Miao et al., 2015), indirect detection (Zhang and Huisingh, 2018, Erian et al., 2011, Dragan et al., 2005, Turkes et al., 2020), direct observation and biophysical measurements (e.g. measuring the tree and vegetation growth) (e.g. Li et al., 2000, Su et al., 2010, Guo et al., 2014) (Table 5).

**INSERT TABLE 5 HERE**

Out of some relevant approaches, on-site field observation and biophysical measurement are labour intensive, costly and time-consuming. Therefore, these tactics are likely applicable over small spatial areas (e.g. field scale). However, they are able to provide first-hand measurements and observation records on the dynamics and conditions on desertification, which can be used for validation of modelling results and remote sensing interpretation.

On-site field observations are also capable of detecting changes (e.g. soil properties, soil-water condition, etc.) induced by desertification that cannot easily be investigated via other methods (Zhang and Huisingh, 2018). Long-term on-site field observations are useful for investigations of desertification mechanisms and the response of desertification to different treatment/mitigation measures (e.g. Li et al., 2000, Su et al., 2010). It is important for desertification evaluation and control to establish permanent field experimental stations. In China, the "*Chinese Desert Ecosystem Research Network* " that comprised with 43 National Research monitoring stations located across the N and NW China (Guo et al., 2014).

Desertification is often assessed via indirect indicators such as its driving factors (e.g. drought, anthropogenic activities), and impacts (e.g. vegetation cover change etc.) (Ajai et al., 2009, Šarapatka et al., 2010, Kust et al., 2011, Jiang et al., 2019a, Jiang et al., 2019b, Gul and Ersahin, 2019). Monitoring of drought/aridification is a common way to evaluate the risk of desertification in regions that have been suffering from drought like countries in Western Asia (Erian et al., 2011, Elagib and Abdu, 1997), in S Asia (Shahid and Behrawan, 2008), E Asia (Wang et al., 2017) and E Europe (Lupu et al., 2010, Mateescu et al., 2013). Many indicators of drought have been developed, such as "*Aridity Index* " (Park et al., 2018), "*Standardized Precipitation Index* " (SPI); "*Standardized Precipitation-Evapotranspiration Index* " (SPEI) and "*Palmer Drought Severity Index* " (PDSI) (Wang et al., 2017). Among these indicators, the SPI has been implemented in the Baribo Basin, Cambodia and showed that the extremely drought events occurred in 1987, 1993, 2001 and 2004 respectively (Sok et al., 2017).

Besides, the indicators of SPI, SPEI and PDSI were applied to investigate the development of drought in the dryness region of NW China between 1960 and 2010 (Wang et al., 2017). Furthermore, the composite index has been applied to assess the desertification risk in the BRI region, which considers multipole natural and anthropogenic factors and thus provides a more comprehensive evaluation of desertification (Hien et al., 2019). For example, the "Environmentally Sensitive Area Index" (ESAI), which is estimated as the geometric mean of four quality indexes on soil, climate, vegetation and management, has been used by (Jiang et al., 2019a) to assess the desertification risk of the C Asia.

"*Remote sensing* " is an effective tool for spotting and distinguishing indicators of various stages of desertification processes through capturing the changes caused by desertification (e.g. changes in vegetation coverage) (Zhang and Huisingh, 2018, Albalawi and Kumar, 2013, Wei et al., 2020). Remote sensing data, often freely accessible, have been applied in the BRI countries for the desertification evaluation (e.g. Li et al., 2013, Liu et al., 2004). Indices like the "*Normalized Difference Vegetation Index (NDVI)* " (NDVI), "*Enhanced Vegetation Index* (EVI)", "*Fractional Vegetation Coverage* " (FVC), "*Lead Area Index* " (LAI) derived from remote sensing datasets are commonly used indicators (Shalaby et al., 2004, Zhang and Huisingh, 2018). For example, the "*Desertification Risk Index* " (DRI), derived from climate factors and NDVI, was developed by Feoli et al. (2000) for desertification evaluation in Turkey and has been successfully applied in the Middle East Lebanon (Dragan et al., 2005).

Remote Sensing technologies have been widely adopted to investigate and understand the changes of soil properties, for example, soil organic matter content (Kumar et al., 2017, Mirzaee et al., 2016) and soil texture (da Silva Chagas et al., 2016, Wu et al., 2015), further improving the capability of remote sensing in desertification detection. However, Remote Sensing technology is subject to inaccuracy. For example, the NDVI and other vegetation information-based methods often overestimate desertification in sparsely vegetated areas mainly owing to the unsteadiness of seasonal vegetation changes and the intensity of precipitation, and the rainstorm-caused severe effects (Dawelbait and Morari, 2008, Wessels et al., 2012, Wei et al., 2020).

Some models have been employed for evaluating the desertification in the BRI countries that are the soil erosion / desertification models such as the "Revised *Universal Soil Loss Equation* " (*RUSLE), "Mediterranean Desertification and Land Use" (MEDALUS)* . The*RUSLE,* developed by Renard (1997), estimates soil erosion rates driven by "*Rill and Interill Erosion* " based on factors including, "*Rainfall Erosivity* ", "*Soil Erodibility* ", "*Topography* ", "*Vegetation Cover* " and "E*rosion Control* ". That model has been popularly applied worldwide to assess soil erosion rates through the cascade of hillslopes study area (Borelli et al., 2017, Li et al., 2020). The model has also been adopted in the BRI countries, Myanmar (Tun et al., 2015), Thailand (Wijitkosum et al., 2013) and China (e.g. Sun et al., 2014, Fu et al., 2011, Li et al., 2020). Whilst, the *MEDALUS* model was developed during the "*MEDALUS EU-funded project"* (Kirkby et al., 1998) and can be effectively used to identify areas of desertification, in relating to various parameters (including "*landforms, soil, geology, vegetation, climate and human actions* "). The *MEDALUS* model was developed for the Mediterranean climatic conditions, such as in Greece (Karamesouti et al., 2018). It has now been widely applied in the BRI countries outside the Mediterranean region such as Iran (Zehtabian et al., 2005, Sepehr et al., 2007) and Thailand (Wijitkosum, 2016).

Another type of model approach is via climate circulation models, which were applied in the BRI area. For example, the "*National Centre for Ocean-Land-Atmosphere Studies* " developed the Atmospheric General Circulation Model (Xue, 1996), namely the "*Community Atmospheric Model Version 3* " (CAM 3) to assess climatic change and its possible impacts on desertification (Jin et al., 2012). The "*NationalCentre for Ocean-Land-Atmosphere Studies* " also further adopted some other atmospheric general circulation models, including a biosphere model by Xue (1996), which tested the response of regional climate to the desertification in the Mongolian Plateau. Other modelling results found that the surface water and energy balance influenced by desertification. The CAM3 modelling results also demonstrated that dryness level in C Asia was closely related to declined wind velocity and decreased evaporation upstream from the Mediterranean Sea, Black Sea, and Caspian Sea in Boreal Winter (Jin et al., 2012). Whilst, the "*Intergovernmental Panel on Climate Change* " (IPCC) models (Doutreloup et al., 2011, Miao et al., 2015) also reported that mean temperature in the Province of Binh Thuan, SE Vietnam was projected to rise by about 1.6 °C (over 2046-2065) and 2.5 °C (over 2081-2100) and the area is likely to suffer from extreme temperatures and extreme rainfall events (Doutreloup et al., 2011).

Most of contemporary models either simulate only one form of desertification (i.e. soil erosion) or evaluate desertification through prediction of climate change. Few quantitative models have been developed to directly assess the desertification status. To the authors' knowledge, the MEDULAS is the only model that can be used to quantitatively assess the desertification condition. The model is applied under the empirical research perspectives, which constraints its capability of reproducing different desertification processes and the response of these processes to natural and socio-economic factors such as climate condition (precipitation, temperature), vegetation growth, land use, human population etc. (Khachatryan, 2013, Li et al., 2017, de Vente et al., 2013). Unfortunately, we have to understand that these tools and models are still having factual limitations. For example, they have an intensive input data that limits their application because of lacking sufficient data support (Li et al., 2017). Field investigations are appropriate for an exhaustive understanding on the processes and mechanisms of desertification over a small area that is beneficial for the development of desertification models. Indirect detection, unlike field investigations, assesses desertification situation based on relevant indicators, which, however, are sometimes not available. Remote sensing is suitable for detection of desertification indicators over a large area, given that remote sensing images have large spatial coverage. Their applicability is often restricted by the technical issues, such as the accuracy and resolution of the images (Albalawi and Kumar, 2013). Quantitative and mathematical models can be adopted to assess and/or predict desertification situation at various spatial scales. The comprehensive desertification model is still rare. Some models that incorporate the reciprocal relationships among natural and socio-economic factors and their influences on desertification are still desirable. Besides, the models often require massive input data, which limit their application in places without sufficient data support. Overall, the desertification evaluation methods are of their own characteristics and applicability (Table 5), and the selection of methods should be based on an evaluation of the nature of research and data availability.

## 6. Conclusion

In this article, we studied the desertification and its control in the countries associated with the BRI initiative proposed by China in 2013, via an extensive review of literature. We argued that the desertification has been widely spread in the BRI countries, particularly in the Central Asian countries, despite quantitative assessment and prediction of desertification is still limited. We also found that the most important factors of desertification by natural and anthropogenic processes are dry climate condition and mis-land-use/management respectively. Anthropogenic (human-induced) activities are a crucial driving force for land desertification in the BRI countries, while natural factors dominated in some dryland regions. However, the relative importance of natural and anthropogenic factors has yet been (quantitatively) assessed for most of the BRI countries.

Desertification in the BRI region has a series of negative impacts on socio-economy and eco-environment, mainly including loss of GDP, loss of productive land and regional climate. Most of the BRI countries have recognized the desertification issue and have ratified the UNCCD and worked out the NAPs. The comprehensive desertification mitigation/conservation programmes are still lacking. BRI countries are therefore encouraged to work together under trans-national or cross-boundary cooperation framework to combat desertification. Research methods employed for desertification evaluation include quantitative approaches (e.g. via mathematical models), indirect detection, and direct observation and biophysical measurement (e.g. measuring the tree and vegetation growth). They have their own characteristics and applicability, and the selection of methods should be based on an evaluation of the nature of research and data availability.

Overall, the desertification situation and their driving mechanisms should be thoroughly evaluated for the BRI region. The all-inclusive and rational conservation measures should be recognised and implemented, in prior to lessen the influence of climatic change and possible human interventions under the BRI framework.

**Author contributions**

F. Chan and P. Li conceived the idea and designed the research, P. Li, Y. Zang and F. Chan produced figures and tables, completed the literature analyses and the draft of the article. P. Li, F. Chan and J. Wang refined the manuscript and checked the figures and tables.

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**Table 1** Desertification situation in different BRI countries summarized from some most representative and selective literature

| **Country** | **Desertification area** | **Study period** | **Source** |
|---|---|---|---|
| China (Eastern Asia) | Desertified areas have been extended from 1.37 $\times 10^5$ $km^2$ to 3.85 $\times 10^5$ $km^2$ during 1950s to 2000 and decreased by 1.37 $\times$ $10^3$ $km^2$ from 2000 to 2010. In 2014, the land surface area 2.16 $\times 10^6$ $km^2$ was desertified in China. | n/a | (Zhang and Huisingh, 2018, Tao, 2014;Cheng et al., 2018) |
| Mongolia (Eastern Asia) | 90% of Mongolian territory is vulnerable to desertification, and 76.8% of land has been desertified to varying degrees | n/a | (Batjargal, 1997, Wei et al., 2020) |
| Vietnam (ASEAN) | 7.5 $\times 10^4$ $km^2$ are affected directly by desertification | n/a | (Yan, 2015, Anh et al., 2006) |
| Thailand (ASEAN) | Over 70% area in Huay Sai that is subjected to a high-risk level of desertification | 1990, 2010 | (Wijitkosum, 2016) |
| Kuwait (Western Asia) | Mean annual desertification land surface area rate reached at 285 $km^2$ between middle 1970s and middle 1990s | n/a | (Al-Awadhi et al., 2003) |
| Turkey (Western Asia) | Around 1.09 $\times 10^5$ $km^2$ land surface area categorised as desert, and around 374.4 $km^2$ that is threatened by desertification and dishabituations. | n/a | (Haktanir et al., 2004) |

| Country | Desertification area | Study period | Source |
|---|---|---|---|
| Iran (Western Asia) | Dry land covers over 85% the country's land, and desertified and desert lands cover $3.4 \times 10^5$ $km^2$ | n/a | (Sepehr et al., 2007) |
| Oman (Western Asia) | Ninety five percent of land is either climate desert or directly affected by desertification. | n/a | (Al-Balooshi and Charabi, 2012) |
| Iraq (Western Asia) | Areas of desertification exceed 92% of the total land surface area | n/a | (Haktanir et al., 2004) |
| Afghanistan (South Asia) | 75% land surface area of Afghanistan is vulnerable to desertification | n/a | (NEPA, 2008) |
| India (South Asia) | In India, total land surface area under desertification is $8.1 \times 10^5 km^2$ | 2003-2005 | (Ajai et al., 2009) |
| Pakistan (South Asia) | $6.24 \times 10^5$ $km^2$ (over 78% land surface area in Pakistan) are susceptible to desertification | n/a | (Hussain and Irfan, 2012) |
| Uzbekistan (Central Asia) | Over 59% of the land surface area is decertified in Uzbekistan | n/a | (Gringof and Mersha, 2006) |
| Kazakhstan (Central Asia) | Over 75 % of the country's territory is subject to degradation and desertification | n/a | (Issanova et al., 2014) |
| Turkmenistan (Central Asia) | 66.5 % of the territory has been subject to human-induced desertification | n/a | (Gringof and Mersha, 2006) |
| Tajikistan (Central Asia) | 97.9% of the country's land experiences soil degradation | n/a | (Nekushoeva and Akhmadov, 2008) |
| Armenia (Russia and SC) | 80% of the Armenia's land surface area is subject to desertification | n/a | (KHACHATRYAN, 2013) |
| Russian Federation (Russia and SC) | Land surface area that has been desertified, the areas currently suffering desertification, areas are at risk of desertification - account for $1.25 \times 10^6$ $km^2$ | 1996-2000 | (Kust et al., 2011) |

**Table 2** Changes of in desertification situation in the BRI countries.

| **Country/region** | **Change of desertification area** | **Study period** | **Source** |
|---|---|---|---|
| China (Eastern China) | Desertified areas enlarged from $1.37 \times 10^5$ km$^2$ to $3.85 \times 10^5$ km$^2$ during 1950s to 2000 and decreased by $1.37 \times 10^3$ km$^2$ from 2000 to 2010. In 2014, the desertified area in China was $2.16 \times 10^6$ km$^2$. | 1950-2000 | (Zhang and Huisingh, 2018) |
| Myanmar (ASEAN) | The dryness region in Myanmar, the mean annual soil erosion rate in 2012 increased at three folds compare to 2000. | 2000, 2012 | (Tun et al., 2015) |
| Kazakhstan (Central Asia) | Since the 1960s, land desertification has increased 10–12%. | 1960s-2000s | (Tokbergenova et al., 2018) |
| Kuwait (Western Asia) | From mid-1970s to mid-1990s, sandy desertification has expanded from 8,900 to 14,600 km$^2$, with a mean annual loss being 285 km$^2$. | middle 1970s- middle 1990s | (Al-Awadhi et al., 2003) |
| Cyprus (Western Asia) | Percentage of desertification-prone areas is likely to expand from 57% to 70.4% between 2008 and 2050. | 2008-2050 | (ClimateChangePost, 2018) |
| Turkey (western Asia) | Desertification may be accelerated in the future given a hotter, drier climate has been projected for Turkey. | 21$^{st}$ century | (Bayram and Öztürk, 2014) |
| South Asia | Most of the climate models projected a dry-season precipitation decline and monsoon precipitation increase in Southern Asia, which implies higher land degradation risk in the future. | n/a | (Ahren and Dobler, 2015) |

| Country/region | Change of desertification area | Study period | Source |
|---|---|---|---|
| Central Asia | Under the RCP 8.5 scenario in IPCC report, which has found that Mid and North Central Asia and NW China (besides Xinjiang Province in China and the Mongolian Plateau) is likely to speed up desertification. | 2006-2100 | (Miao et al., 2015) |
| Hungary (Central and Eastern Europe) | Projected future climate change of increased temperature and decreased precipitation will further enhance the desertification in SE European countries. | n/a | (Kertész, 2016) |

| Country | Natural factors | Anthropogenic factors | Dominated by | Source |
|---|---|---|---|---|
| China (Eastern Asia) | Dry climate condition | Non-suitable human activities (e.g. agricultural reclamation, grazing) | non-sustainable anthropogenic activities | (Zhang and Huisingh, 2018) |
| | Dry climate | Socioeconomic forces (Rural Population, Net income, farmlands and arable lands, livestock grazing, deforestation and agricultural activities are barred, afforestation and vegetation re-enhanced) | Socioeconomic forces | (Feng et al., 2015) |
| Mongolia (Eastern Asia) | Dry climate | animal husbandry, grazing, crop cultivation, deforestation, mining and inadequate waste management | n/a | (Batjargal, 1997) |

| Country | Natural factors | Anthropogenic factors | Dominated by | Source |
|---|---|---|---|---|
| Myanmar (ASEAN) | Dryness and hot weather conditions | over-grazing, unsuitable crop management practices | n/a | (Tun, 2000, Tun et al., 2015) |
| Vietnam (ASEAN) | Long dry seasons and short-duration intensive rainfall in the rainy season | Agricultural and forestry production | n/a | (Anh et al., 2006) |
| Oman (Western Asia) | Increased Temperature and decreased rainfall | n/a | n/a | (Alvi, 1995) |
| Bahrain (Western Asia) | Low rainfall and high temperature | inappropriate land and water use and vegetation reduction | n/a | (Elagib and Abdu, 1997) (Alvi, 1995) |
| Kuwait (Western Asia) | Climatological processes (low rainfall, intensive rainfall, strong winds during dry season) and geological processes. | Over-grazing, vehicles, camping and over-exploitation of sediment | human population | (Al-Awadhi et al., 2003) |
| Turkey (Western Asia) | Dry climate | Vegetation reduction, grazing, agriculture, unsuitable irrigation techniques, soil salinization, and uncontrolled wild type plants picking | Inappropriate farming, grazing activities, and de-vegetation | (Haktanir et al., 2004) (Camci Çetin et al., 2007) |
| Syria (Western Asia) | Drought | Misuse of natural resources | n/a | (Haktanir et al., 2004) |
| Lebanon (Western Asia) | Drought | Deforestation, over-grazing, urbanization, construction of infrastructures (e.g. roads), poor agricultural and cultivation approaches, disproportionate use of chemicals, and economic development | n/a | (Haktanir et al., 2004) |
| Iraq (Western Asia) | Dry climate, north-westerly winds | Population growth, decreased forest cover, pastures, and land productivity, Urban expansion | n/a | (Al-Saidi and Al-Juaiali, 2013) |

| Country | Natural factors | Anthropogenic factors | Dominated by | Source |
|---|---|---|---|---|
| Cyprus (Western Asia) | Summer droughts, steep slopes | Land use changes, abandonment of marginal land, forest fires | n/a | (ClimateChangePost, 2018) |
| Abu Dhabi Emirate, United Arab Emirates (Western Asia) | Drought, wind erosion, Nebkha Dunes, water erosion | Water logging, vegetation reduction, compaction, land filling and mining | Wind erosion | (Abdelfattah, 2009) |
| Iran (Western Asia) | Dry climate, erosion (by water and wind) | population pressure, misuse of freshwater resources , over-grazing | n/a | (Amiraslani and Dragovich, 2011, Gu et al., 2015) |
| Sri Lanka (Southern Asia) | periodic droughts | Cultivation, deterioration of forest | Chena cultivation, deterioration of forest | (Tennakoon, 1980) |
| Afghanistan (Southern Asia) | Drought, topography, Geology | steep slope farming, de-vegetation and unsustainable use of scrub and grasslands | n/a | (Saba, 2001, NEPA, 2008) |
| Bangladesh (Southern Asia) | Drought, change in coastal morphology, river bank erosion, sedimentation on agricultural land, salinity, land fragmentation | Shifting cultivation, faulty cultivation practice, use of pesticides, mining in agricultural land, irrigation, overexploitation of biomass | n/a | (Department of Environment Bangladesh, 2005) |
| Nepal (Southern Asia) | n/a | cultivation of marginal lands, livestock grazing and biomass cover loss | n/a | (Paudel et al., 2009) |
| Pakistan (Southern Asia) | Drought, soil erosion (water erosion and wind erosion) | Deforestation, overgrazing, waterlogging and salinity, unsuitable management practices, urbanization and industrialization | Unsuitable land management practices | (Anjum et al., 2010) (Hussain and Irfan, 2012) |

| Country | Natural factors | Anthropogenic factors | Dominated by | Source |
|---|---|---|---|---|
| Armenia (Russia and surrounding countries) | Droughts, hot winds, landslides, submergence, floods, natural salinization | Urban development activity, Inadequate use of agricultural equipment, Deforestation, mining, soil contamination and disruption of biodiversity | n/a | (MNP, 2002) |
| Georgia (Russia and surrounding countries) | Droughts, wind erosion | Cultivation, grazing, deforestation and irrigation | n/a | (Davitashvili et al., 2009) |
| Serbia (Central and Eastern Europe) | Droughts | Forest fires, increased surface exploitation of non-metals, raw materials extraction and increased demands for natural resources below the land surface, the establishment of industrial waste tips | n/a | (Gajić and Đeković, 2005) |
| Hungary (Eastern Europe) | Droughts | n/a | n/a | (Kertész, 2016) |

**Table 4** Contemporary countermeasures for desertification control in the BRI countries

| Country | title | year | objectives | strategy/measures | Impacts/benefit | Source |
|---|---|---|---|---|---|---|
| China (Eastern Asia) | Three—North Shelterbelt project | 1978 | To protect the cropland from being damaged by wind erosion and stabilize by the leeside of sand dunes areas (that is with milder sandstorms and wind) | n/a | By 2000, over 2.2 X $10^5$ $km^2$ of forests have been re-vegetated and 8.9 X $10^4$ $km^2$ of prairies have been restored | (Zhang and Huisingh, 2018) |

| Country | title | year | objectives | strategy/measures | Impacts/benefit | Source |
|---|---|---|---|---|---|---|
| | Beijing and Tianjin Sandstorm mitigation Project | 2000 | To control sand storms in NE Chinese cities (e.g. Beijing) and surrounding areas | n/a | Approximately $2.6X10^4$ $km^2$ of cropland were re-vegetated and afforested with new grown suburbs and trees during 2000-2010, with a relatively high survival rate | (Zhang and Huisingh, 2018) |
| | Grain-for-Green project | 1999 | To constraint traditional agricultural activities on ecologically fragile and land areas under desertification; To control desertification in local areas (e.g. districts and villages); To reduce the desertification impacts in the downwind areas, such as in industrial regions and cities that locate in E and S China | n/a | During 1999-2012, $3.67$ X $10^4$ $km^2$ of cropland and degraded steppe in dryness areas that were no longer used and $5.13X10^4$ $km^2$ suffered desertification that were restored. Around 8 X $10^4$ $km^2$ of desertified land were restored and $2.67X10^5$ $km^2$ of shelters and wind belts were established | (Zhang and Huisingh, 2018) |
| Mongolia (Eastern Asia) | "Green Great Wall" forest construction plan | 2005 | To control desertification and increase vegetation coverage | Build 3000 km long and 0.6 km wide forest belt | n/a | (Liu et al., 2018) |

| Country | title | year | objectives | strategy/measures | impacts/benefit | Source |
|---|---|---|---|---|---|---|
| Myanmar (ASEAN) | Rural Land Development Department | 1953- | To rehabilitate forests, principally in the Dry Zone | Plantations in Mount Popa. | The prevailing insecure conditions hampered most of the efforts | (Tun, 2000) |
| | A concerted drive to regreen the Dry Zone | 1971 | To plant in the Dry Zone | Locations that were considered to have the potential to regenerate naturally were put under protection. | The most visible impact was on Mount Popa, where 90% of the forests that exists today regenerated naturally | (Tun, 2000) |
| | Regreening of the Central Dry Zone | 1992 | To establish 50,000 acres of plantation on degraded lands, over a period of five years, to supplement local fire wood demands | n/a | n/a | (Tun, 2000) |

| Country | title | year | objectives | strategy/measures | Impacts/benefit | Source |
|---|---|---|---|---|---|---|
| | The Dry Zone greening department | 1997 | (1) to increase green area in the Dry Zone; (2) to provide forest products for rural residents; (3) to improve knowledge exchange and engage with public participation on ecological conservation and understanding of desertification; (4) to endorse socio-economic development in Rural area; (5) to improve sustainable agriculture; (6) to stop desertification. | Establishment of forest protection and water resources management | n/a | (Weine, 2013) |
| Pakistan (Southern Asia) | Sustainable Land Management to Combat Desertification in Pakistan | 2008-2009 | To control land degradation and desertification; To protect ecosystems and improve ecosystem services that crucial for poverty elimination | n/a | n/a | (Anjum et al., 2010) |

| Country | title | year | objectives | strategy/measures | Impacts/benefit | Source |
|---|---|---|---|---|---|---|
| Hungary (Central and eastern Europe) | The National Climate Change Strategy 2008-2025 | n/a | To reduce greenhouse gases emission and to prevent their increase | Prevent the unfavourable ecological and socio-economic effects (e.g. desertification) of climate change and improve the adaptability of public to the consequences of climatic effects | n/a | (Kertész, 2016) |
| | The New Hungarian Rural Development Plan | 2007- 2013 | To improve the environment quality, To improve ecological conditions through forest plantation. | n/a | n/a | (Kertész, 2016) |
| | The National Agri-Environmental Programme | n/a | To improve the environment quality, To improve ecological conditions through forest plantation. | n/a | n/a | (Kertész, 2016) |
| | The National Drought Strategy | 2006- | To provide an agenda for promoting sustainable ecosystems management in the drought-prone and arid areas | Drought prevention and control | n/a | (Kertész, 2016) |

**Table 5** Comparison of methods used for desertification evaluation in the BRI countries.

| Method | Application |
|---|---|
| Model | Estimation of the desertification situation (RUSLE, MEDALUS)<br>Prediction of the factors (e.g. rainfall, air temperature) impacting desertification (CAM3, CCSM3.0, I |

| Method | Application |
|---|---|
| Indirect detection | Identifying desertification via an assessment of desertification indicators, and remote sensing technique |
| Field investigation | Assessing desertification state based on direct field observations |

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