ORIGINAL PAPER

The consequences of soil degradation in China: a review

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Abstract

More than 40% of China's arable land is degraded. This paper reviews the direct and indirect consequences of soil degradation in China. Soil degradation has observable and measurable impacts, which include soil nutrient loss, salinization, acidification, and desertification. It also has a number of indirect consequences, in particular, a reduction of the agricultural output due to a drop in soil nutrient; an increase in the frequency and magnitude of floods and landslides; a decline in livestock production due to a decrease in grass density available to roaming livestock; an intensification of dust storms and sandstorms which affects health, the productivity of the land, and visibility; and a faster accumulation of silt in dams, which damages their structure, reduces their water storage capacity, and compromises their original functions, in particular their electricity generation capacity.

Highlights for public administration, management and planning:

- China only has 0.21 hectares of agricultural land per person, about half of the world's average, but more than 40% of China's arable land is degraded.
- Direct (soil salinization and acidification, desertification) and indirect (reduction of agricultural output and livestock production, weakened ecosystem services, increased dust and sandstorms, flood and landslides and accumulation of silt in dams) consequences of soil degradation is discussed.

Keywords
Soil degradation,
agricultural output,
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1 Introduction

Agriculture is one of China's most important economic sectors. As much as 35% of its labour force is involved in agriculture, a sector that provided 7.9% of total Gross Domestic Product in 2017 (World Bank 2018). China's agricultural sector is very productive. Since 1980s, China's per capita agricultural land has remained stable at the (low) average of 0.21 hectare per person, about half of the world's average (Fukase & Martin 2016).

Yet, the per capita calorie intake grew from 2,163 kcal to 3,036 kcal, a much faster rate than the world average, while the population grew by 31% during this period (Word Bank 2018). Cereal yields have increased from 2,937 kg/ha in 1980 to 6,029 kg/ha in 2016, an increase of 105% (compared to a world average increase of 73%) (World Bank 2018). With 13.4% of the world's land under cereal production, China is able to produce 20 % of world's cereals and feed 18% of the world's population (World Bank 2018). However, such high productivity comes at a cost. This increase has only been possible through a very large and growing use of fertilisers: Chinese farmers use an average of 305 kilograms of nitrogen fertiliser per hectare per year – more than four times the global average (Harris 2018). This in turn has contributed to the soil degradation. China is now subjected to the world's most severe soil degradation, with over 40% of its land area being affected by erosion (China Daily 2014). Most erosion takes place in the mountainous areas of central China, with the Loess Plateau being the most affected areas (Rao et al., 2015). Soil degradation has broad consequences. One direct consequence of soil degradation is the reduction of land usable for agriculture and the decrease of land productivity, because the loss of surface soil layers with rich organic matter and nutrients will decrease the fertility and moisture-holding capability of the soil. Other direct consequences are soil salinization, soil acidification, and desertification (LADA 2010). These processes often occur on marginal soil in the less densely inhabited areas of the north and the west. There is little fertile soil in these regions, so any further degradation of the little fertile land that remains has great influence on grain output and livestock production, and carries considerable negative consequences for the people.

Perhaps of even greater importance are the indirect impacts, which also affect the densely populated and economically prosperous eastern provinces. Indirect impacts go beyond the site-specific ones directly observable in the field, and include dust storms, flooding, landslides, the siltation of dams which reduces hydroelectric output, and a reduction of agricultural output. These carry high economic costs, and affect the whole country. Since China already has little land per capita, a reduction of farmland caused by its mismanagement, is particularly alarming.

Land degradation has major impacts on land productivity, people's livelihoods, and environmental conditions. LADA (2010) estimated that the annual direct economic costs attributable to land degradation reach CNY 540 billion, while the indirect costs are approximately twice that amount, reaching in some cases as much as 10 times the amount of the direct costs.

The aim of this paper is to review the information available on the direct and indirect consequences of soil degradation in China, and to give a picture of the general conditions in the country. China is a very large country with a great diversity in terms of geomorphological conditions and kinds of soils, as well as land use types and the socio-economic conditions that affect soil use. The aim of the paper is not to go into detail about any particular region, soil type, or land use, but to give a broad background of the situation in the country. The paper is based on a review of reports and journal articles published predominantly during the 2010s in English.

2 The direct consequences of soil erosion

2.1 Soil Salinization

By definition, saline soil contains a high enough concentration of soluble salts to influence plant growth (Li et al. 2016). However, salinity becomes a problem when the high levels of sodium accumulated in the root zone start to interfere with plant growth. Too much salt stresses the plant by preventing the roots from absorbing water from the soil, and excessive amounts of salt in the transpiration stream can damage the cells of the transpiring leaves, further affecting plant growth (McKersie & Lesheim 2013). This phenomenon is known as the salt-specific or ion-excess effect of salinity (Greenway & Munns 1980). In its early stages, the dissolved salt content decreases soil productivity by affecting the metabolism of soil organisms, but in the long run it ruins the vegetation and other organisms living in the soil, essentially transforming arable land to infertile, desertified lands (McKersie & Lesheim 2013).

Soil salinization may be caused by different factors. High soil salinity levels may be attributed to physical or chemical weathering, as well as transport from parent material, geological deposits, or groundwater. The accumulation of salts can also be caused by underlying parent rock constituents, such as carbonate minerals and/or feldspars, or by the one-time submergence of soils under seawater (Salama et al. 1999). Wind and air may also cause the accumulation of salts in coastal zones. The inland wind can carry the salt from the sea over long distances as spindrift; or the salt can fall to the ground with the rainwater after being car-

Table 1 Salt tolerance of crops in the different regions in China

		Salinity [%]			
Region	Soil depth	Lightly inhibiting growth	Moderately inhibiting growth	Severely inhibiting growth	Preventing growth
North-east	0-50cm (SO_4^{2-})	0.3-0.5	0.5-0.7	0.7-1.2	
Shandong Province	surface soil layer (total salt content)	<0.2	0.2-0.4	0.4-0.8	
	100cm (total salt content)	<0.1	0.1-0.3	0.3-0.5	
North China	0-20cm (CL-SO_4^{2-})	0.15-0.25	0.25-0.40	0.40-0.60	
North-west	0-30cm (SO_4^{2-})	0.4-0.8	0.8-1.2	1.2-2.0	>2.0
	0-100cm (SO_4^{2-})	0.3-0.6	0.6-1.0	1.0-1.5	>1.5
Xinjiang Province	0-30cm (total salt content)	0.554-0.727	0.727-0.866	0.866-1.345	>1.345
	0-100cm (total salt content)	0.391-0.491	0.491-0.597	0.597-0.895	>0.895

Source: MEP (2003), Table B3

ried by the warm north-westerly winds. According to Yang (2006), climate change is another significant driving factor in the salinization of the soil. North and north-east China in particular are becoming warmer and drier, which contributes to the increasing salinization of the region's soils.

The salinized land is mainly distributed in areas with a higher groundwater table and higher evaporation. In arid areas, saline soils may be formed through evaporation and the lack of rainfall to flush the soils. Waterlogging may also cause salinization: in semi-arid regions where waterlogging is followed by drought, when rain falls, the water dissolves the salt naturally found in the soil and brings it to the surface. When the water evaporates, the salt remains on the surface (Mao et al. 2002). In addition, the water used for irrigation (whether river or groundwater) also contains salts, which remain behind in the soil after the water has evaporated. Furthermore, impeded drainage in areas irrigated by continuous flooding (as is the case with paddy rice) causes secondary salinization (LADA 2010). In the oasis basin of Xinjiang in north-west China, the area of salinized soil makes up about 1.05 million ha, which accounts for 33.4% of the total agricultural land in the region, and research has found that the salinity of this area is trending upwards.

According to Zhang et al. (2014), the area of salinized soil in China is about 36.93 million ha, which accounts for about one third of the total arable land. Studies showed that when the concentration of salt ions in the soil exceeds 8 g per kg of soil, it can severely damage or prevent crop growth on farmlands (Zhang et al. 2014). Table 1 shows the salt tolerance of crops in China's different regions.

2.2 Soil Acidification

Soil pH is a critical measure for plant growth. Crops generally thrive in slightly acidic (with a pH value lower than 7) or neutral (with a pH value of 7) soils. When the pH value decreases, the soil becomes susceptible to diseases and pests that slow down plant growth. Heavily acidic conditions also cause toxic metals to leak into nearby bodies of water. Moreover, soil acidification can help to increase the accumulation of some heavy metals like Cd in food crops (Hvistendahl 2010).

During the early 1980s, a national soil survey determined the pH values of topsoils. To understand the changes in soil acidity that have occurred between the 1980s and the 2000s, Guo et al. (2010) "collected all published data on topsoil pH from 2000 to 2008 and compiled two (unpaired) data sets (1980s versus 2000s) on the basis of six soil groups according to geography and use, with two subgroups per soil group: cereal crops and cash crops" (Guo et al. 2010:1008). Both cropping systems—especially cash crops like greenhouse vegetables that have spread rapidly since the 1980s—received very high fertilizer inputs compared to other agricultural systems (Guo et al. 2010). The results showed a considerable acidification of all topsoils, with an average pH decline of 0.13 to 0.8. In all other soil groups, acidification has been more significant in cash crops (pH decreased by 0.3 to 0.8) than cereals (a drop of 0.13 to 0.76). In some areas, the pH values dropped by 0.8 over two decades, with some soils growing high-input cash crops reaching a pH of 5.07. As a comparison, when soil is left under natural conditions, it takes at least 100 years to reach this level of acidification (Gilbert, 2010). As the scale is logarithmic, a pH decrease of 0.3 corresponds to a doubling in hydrogen ion activity (Guo et al. 2010). Acidification has already decreased crop production by 30-50% in some areas.

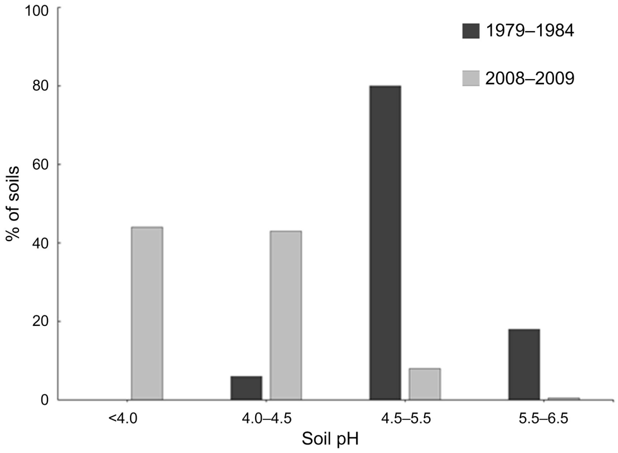

Fig. 1 Comparison of pH of natural soils in Foshan (Guangdong Province) during 1979–1984 and 2008–2009 (source: Hou et al. 2012)

Zhang Fusuo, a professor of plant nutrition at China Agricultural University in Beijing, said that *"in the south, the heavy use of fertilizers has pushed the pH to 3 or 4 in some places. Maize, tobacco, and tea cannot be grown. This is a long-term effect"*. He claimed that if the degradation of soil continues, some regions could see the soil pH drop to as low as 3 in the long run, and warned that *"no crop can grow at this level of acidification"* (in Tan 2010).

Hou et al. (2012)'s study in Foshan (Guangdong Province) showed that 90% of the soil samples in the study area had a pH <4.5, and only 8% of soils had a pH within the range 4.5–5.5 in the year 2008 and 2009. This can be compared to 80% of the soil samples that were in that range during 1979–1984 (Figure 1).

2.3 Desertification

According to Yongli Zhang, deputy head of the State Forestry Administration, “land desertification poses the most serious threat to ecological development in China”. According to Zhang, China now has 261 million ha of soil that is classified as undergoing desertification. This corresponds to about 27.2% of the country’s mainland, and is spread across 528 counties in 18 provinces, autonomous regions, and municipalities, directly affecting some 400 million people (Hao 2016).
The process of desertification is due to various factors, both natural and man-made. Natural causes include wind erosion, water erosion, and freeze-thawing erosion, which in China have caused the desertification of 183.2 million ha, 25.52 million ha, and 36.35 million ha of land, respectively (Figure 2). Desertification is mostly observed in the provincial regions of Xinjiang, Inner Mongolia, Tibet, Gansu, and Qinghai, which together account for 95.48% of the total area of desertified lands in China (SFA 2011).

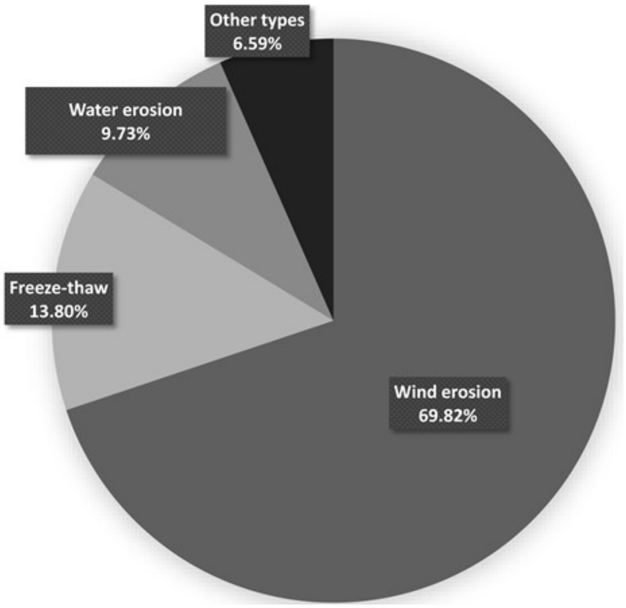

Fig. 2 Distribution of different desertification types (source: SFA 2011)

Feng et al. (2015) looked at the natural and man-made causes of desertification. Using a pooled regression model based on panel data, Feng et al. (2015) assessed the effects of climate change and human activities on the desertified areas of Xinjiang, Inner Mongolia, Gansu, and Ningxia Hui between 1983 and 2012. The results showed that “livestock number, farmland area, road construction, and mean annual temperature were significantly positively related to the change in the area of desertification, accounting for 30.8, 21.9, 4.1, and 14.6 per cent of the total effect, respectively” (Feng et al. 2015:4) (Table 2). The findings (Figure 3) also revealed that the most dominant driving factors varied across the regions, and so did the solutions. Livestock contributed to desertification in all regions, suggesting that forbidding grazing would be an effective approach to ecological restoration. On the other hand, afforestation has yielded mixed results: while it was an effective way to restore soils in Gansu and Ningxia Hui, it actually accelerated the desertification process in Inner Mongolia and Xinjiang (Delang and Wang 2013; Feng et al. 2015). Indeed, planting trees in arid regions can sometimes result in greater desertification.

Table 2 Regression results for the relationship between the driving factors and the area of desertification, and the contribution of each factor to the changes in the desertified areas (1990-2010).

	Pooled	Stand. error	Contribution [%]
Rural population (× 109 persons)	− 177.5**	− 3.90	10.55
Rural net income (× 106 RMB)	− 690.1*	− 2.74	7.80
Farmland area (× 106 ha)	0.987**	− 3.61	21.87
Livestock number (× 109 head)	11.050**	− 7.24	30.80
Forbidden area (× 106 ha)	− 1.177*	− 2.89	4.20
Cumulative afforestation area (× 106 ha)	− 0.00792	− 0.09	0.08
Length of~roads and~railways (× 106 km)	16.90*	− 3.05	4.06
Mean annual temperature (°C)	39.20$^+$	− 2.14	14.64
Total annual precipitation (mm)	− 5.898$^+$	− 2.33	6.00

Note: “Forbidden area” represents areas where grazing and growing crops were prohibited. Sample size: n = 108. Significance levels: **0.01 , *0.05 , $^+$0.10; Source: Feng et al. (2015)

Sandification has been a source of various problems to the farmers and herdsmen, eventually leading to the impoverishment of the local population and the vicious cycle of people exploiting the envi-

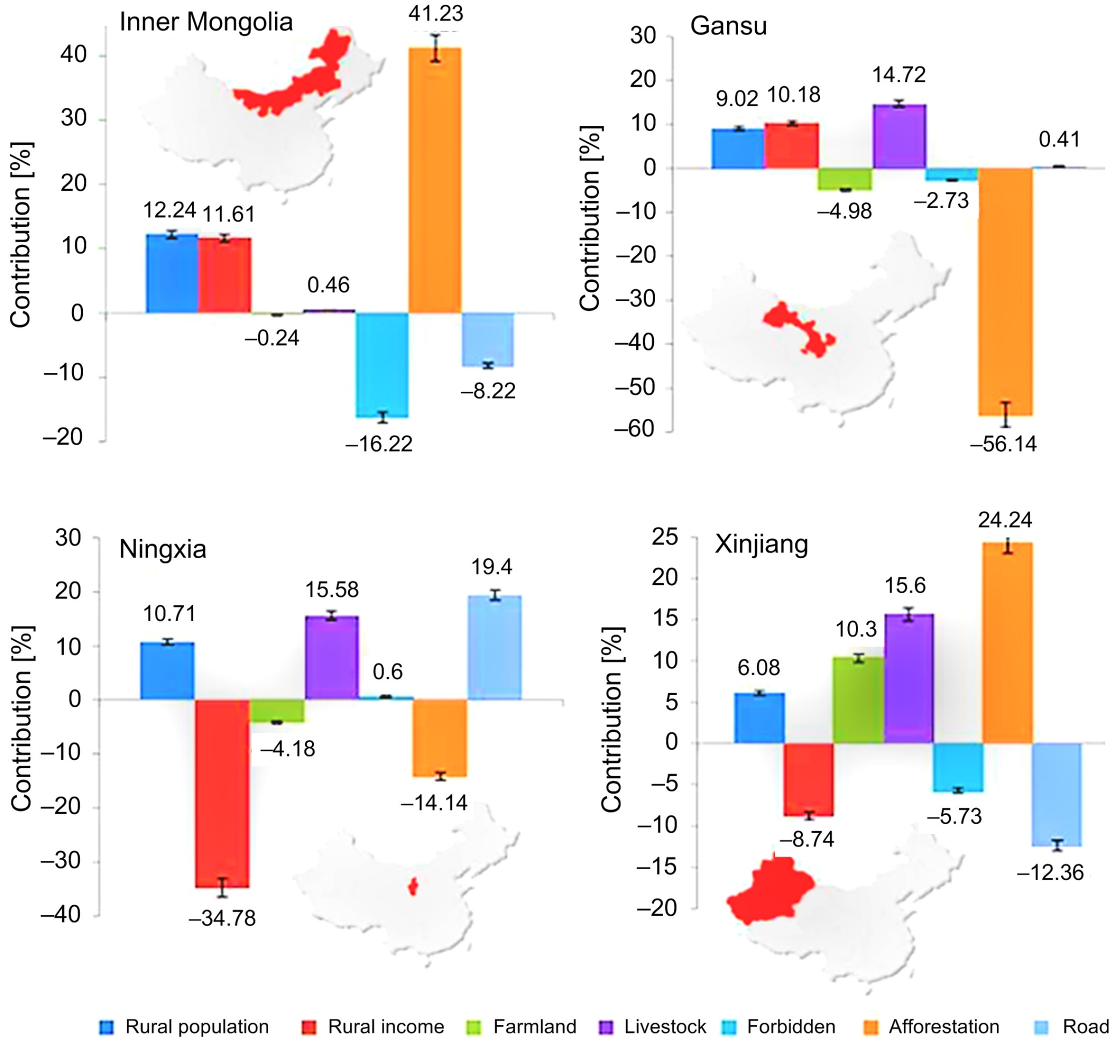

Fig. 3 Contribution rates (%) of the factors affecting desertified areas based on regression analysis results. Note: “Road” represents the length of roads and railways. (source: Feng et al. 2015)

ronment unsustainably to try to maintain their already poor standards of living, which further degrades the environment. LADA (2010) reports how in the northern part of the Yinshan Mountains of Inner Mongolia, wind erosion and sandification significantly hinder agricultural output, animal husbandry, as well as the everyday life of local people. As a result, the Yinshan Mountains are home to 23.4% of the poorest people of Inner Mongolia. In the Chayouhou Banner and Huade County of Inner Mongolia, over 90000 people were forced to give up their homes and move to more livable areas. In the Xihaigu Region of Ningxia Hui Autonomous Region, the combined harmful effects of water erosion and wind erosion have deteriorated the environment so much that 200,000 people have been relocated over the past years (LADA 2010).

3 The indirect consequences of soil degradation

Healthy soils are the backbone of a nation’s economy. Soil degradation has broad consequences, which are felt not only among rural dwellers, but throughout the national economy. I call these the “indirect” consequences of soil degradation. They are now considered for the remainder of this article.

3.1 Reduction of agricultural output

Although there has been a significant improvement in cereal yields over the last few years (Figure 4), it is uncertain whether this upward trend will con-

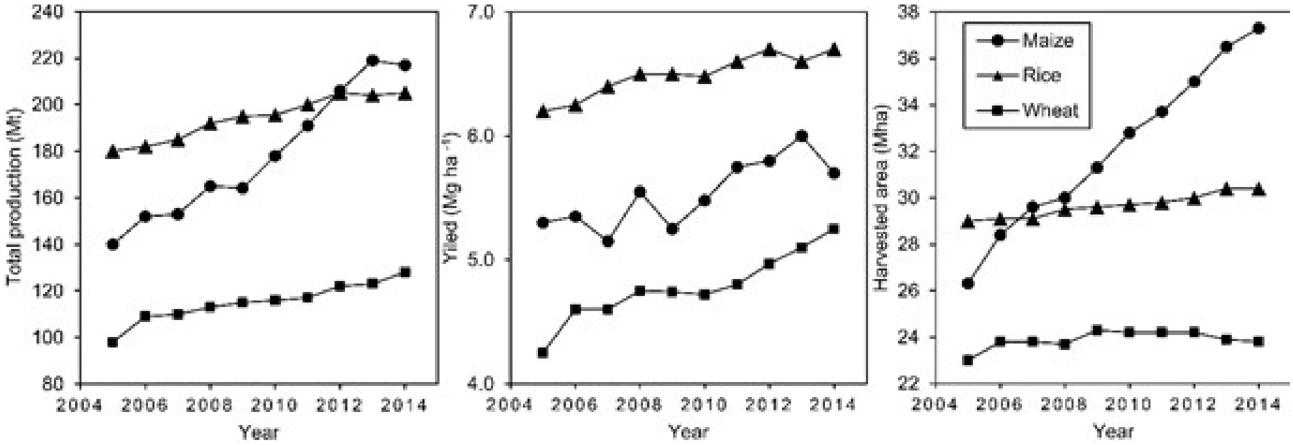

Fig. 4 (A) Total production, (B) average yield, and (C) harvested area of rice, maize, and wheat in China (2005−2014) (source: GYGA 2016)

tinue (Wei et al. 2015). According to an official report released in 2016, China could experience a drop in wheat production for the first time in 12 years (Xu 2016). Li et al. (2013) argued that the future food security of China is challenged by problems such as soil degradation and pollution, the low efficiency of resource use, and the competition for nonagricultural land uses. Indeed, in addition to the degradation of the soil, some of the most fertile agricultural land is being converted to urban uses (e.g. parks, roads, housing, and industrial complexes). Chen (2007) argued that urbanization has led to the irreparable damage of the physical and biotic characteristics of the soil, resulting in the total loss of productivity: in the event of a grain supply emergency, quick reconversion of urban land to crop production would not be possible. The same study also found that urbanization progressed much quicker in heavily populated areas where soils had previously not suffered serious degradation. For instance, the coastal provinces of Jiangsu and Guangdong in south-east China (which, unlike other provinces, were not required to protect some of their land from urban expansion), suffered a loss of almost 30 million tons of grain output in 2003 compared to the grain produced in 1998. The decrease in crop production in these regions primarily occurred due to losing arable land to land development (Chen 2007). Contrasting GYGA's (2016) findings (Figure 4), Wei et al. (2015) looked at the trends of crop yield in China from 1980 to 2008, and found that the main cereal-growing areas across the country have been characterized by yield stagnation. They found that 53.9% of the counties included in the study experienced a significant stagnation in rice yield, followed by maize yield in 42.4% of the counties, and wheat yield in 42% of the counties.

Duan et al. (2011) addressed the consequences of soil erosion on land productivity, as well as the long-term productivity alterations in China's northeastern black soil region using a modified productivity index (MPI) model (MPI is a number between 0 and 1, with 1 indicating highest productivity). Over half of the examined soil samples showed moderate levels of productivity. The MPI model showed that soil organic matter and available water-holding capacity (AWC) were crucial factors affecting stress levels, as both features showed a negative correlation to the severity of soil erosion. The greater the erosion is, the lower the MPI values are. The results imply that with every cm of topsoil affected by erosion, the productivity level of black soils will drop by approximately 1%. In the long run, the erosion of black soil in north-east China may severely limit food production in the area. Duan et al. (2011) concluded that immediate and effective conservation methods should be put into practice to protect the soil and water resources in the region.

If China continues to experience the same rate of soil erosion, an area as large as the islands of Cyprus or Puerto Rico will disappear over the next 50 years—resulting in a 40% drop in food production, according to a study conducted by the country's Ministry of Water Resources, and the academies of science and engineering (Ding 2010). In the same vein, Huang Hongxiang, a researcher from the Institute of Agricultural Resources and Regional Planning, cautioned that China's present focus on production volumes could have a severe impact on its agricultural development. *"If we don't improve the quality of farmland, but only depend on increasing invest-*

ment and improving technology, then—regardless of whatever super rice, super wheat and other super quality crops we come up with—it will be difficult to guarantee the sustainable development of our nation's agriculture." (Watts 2012).

3.2 Damages to grassland resulting in reduced livestock products

Grassland degradation is a process in which the vegetation becomes sparser and shorter, with a lower grass density. Grassland productivity is graded based on the dry matter yield of grassland per hectare per year:

(1) high yield: > 2000 kg of dry matter per ha per year;

(2) fair yield: 1000−2000 of kg dry matter per ha per year;

(3) low yield: < 1000 of kg dry matter per ha per year.

Unfortunately, most grasslands in China produce a low yield. This is particularly the case in the Western and Northern provinces of Tibet, Qinghai, Xinjiang, Gansu and Inner Mongolia (Chen & Fisher 1998). In the late 1990s, low-yield areas accounted for two-thirds of the total, while high-yield areas accounted for just over 10 percent of all grasslands (Chen and Fisher 1998). Unfortunately, the situation has been worsening since then. The case of the Guyuan pastureland in the north-west Hebei Province (on the Bashang Plateau) may be indicative of many other areas in China. In the 1950s, the hay production of the Guyuan pastureland totaled 250-300 kg per year, with a grazing grass coverage of 90% and grass height of 50−100 cm. Chen and Fisher (1998) describes the area as having a fair yield in the late 1990s. By the late 2000s, however, the grass coverage was only about 40% and the grass height 20−40 cm, while the production of hay had decreased to 50−100 kg per annum (LADA 2010). From a high-yield area in the 1950s, the Guyuan pastureland had become a low-yield area by the late 2000s.

A regional scale survey found that, consistent with land degradation processes, the total C and N content and effective cation exchange capacity (ECEC) of the soil also decreased significantly. Consequently, the productivity of grassland decreased. In cases of severe soil degradation, it may be impossible to re-establish the right balance of nutrient stocks in soils (Wu et al. 2008). Lands under heavy grazing pressure may lose their fertility, which in turn increases the soil's susceptibility to wind erosion, eventually turning the area into a desert. Due to the poorer grassland quality caused by soil degradation, herdsmen can only keep hardier livestock breeds such as goats and camels. With the heavy impact of land degradation, the quality of livestock has also decreased. Herders have tried to increase the number of livestock to compensate for their smaller size, which, ironically, resulted in the per head grazing land areas to drop by 50%, leaving livestock in a semi-hungry state for long periods. The result was a drop in the output of livestock and livestock products. For example, in Uxin Banner in Inner Mongolia, the average weight of sheep dropped from 25 kg in 1950s to 15 kg by the early 2000s, while the weight of goats dropped from 15 kg to 9 kg over the same period (LADA 2010).

Similar processes happened to cultivated fields. Lu & Chen (2013) claimed that there was a link between the poor agricultural land and people's poverty in the western counties: poor farmers could not afford to expand production on their existing land, because of the low productive capacity of the land, the poor agricultural infrastructure, and insufficient capital accumulation. Under these conditions, farmers had no choice but to expand their land to increase agricultural output and incomes by turning woodlands, grasslands, and steep lands into farmlands, regardless of these lands' suitability for agriculture. However, the gradual degradation of the quality of the land, together with the expansion of the population, results in a vicious circle which makes it increasingly difficult to raise incomes and use the environment sustainably. Eventually, soil erosion consigned the area into a long-term poverty trap (Lu & Chen 2013). According to LADA (2010), although the north and the west have a population density of only 43% – and 1.76 times as much land – as the eastern areas, the per capita grain production in the north and the west is only 50% of that in the east, their per capita consumption and savings are only 33%, the density of schools is only 49%, and that of clinics is only 8% as high, while the quality of these schools and clinics is poorer (LADA 2010).

3.3 Impacts on Ecosystem Services

Land degradation has led to the reduction of usable grasslands and forest lands, and through the loss, fragmentation, and isolation of natural habitats, to a reduced level of biodiversity. In addition, it has changed the structure of animal populations and communities, reducing the productivity and liveliness of species (through lower birth/survival rates and pest/disease resistance capability, among others), gradually pushing them to the verge of extinction. For example, in Mu Us Sandy Land (in Central China), many animal and plant species have disappeared or suffered a decline in species distribution or population. For instance, there were more than 5 million Mongolian gazelles (*Procapra gutturosa*) living on the grasslands of Inner Mongolia in the 1950s, but their residual population is now less than 300,000; the leopard, wild cattle, and wild camel have almost become extinct; and the populations of the gray marmot, fox, and wolf have dropped significantly (LADA 2010).

Soil degradation, whether caused by drought, salinization, or its over-exploitation, affect the ability of the soil to sustain and regenerate itself (UNESCO 2003). If a pasture becomes severely degraded, the distribution of various plant species will change. In particular, there will be a reduction in the proportion of palatable plant species such as grasses and grass-like plants. Animals whose food supply depends on this vegetation are forced to migrate to other grazing areas. At the same time, many of these animal species are also valuable resources for people, and their disappearance may increase food insecurity and threaten people's livelihoods (Wu et al. 2008).

3.4 Dust and sandstorms resulting from land degradation

Due to "overgrazing by livestock, overcultivation, excessive water use, or changes in climate" (Economy 2011:66), more than a quarter of the total land area of China has been affected by land degradation or desertification. The State Forestry Administration in China stated that the desertification of land is the country's most critical ecological issue, and one that will only be worsened by climate change (Delang 2017).

Dust events in China are associated with two main source areas. The first affected region is the Hexi Corridor and the western Inner Mongolia Plateau, which are covered by the Gobi Desert, wadis, and alluvial fans. Stretching across China and Mongolia, the Gobi Desert is the second largest dust source in the world (and the most important one in China), and eats up 360,000 ha of fertile grassland each year. The second largest dust source is the western Taklimakan Desert, followed by the central area of the Inner Mongolia Plateau and north-eastern China (Wang 2014). Experts attribute Beijing's dusty weather to the desertification of vast areas of grazing lands and plains north of the capital in the Autonomous Region of Inner Mongolia, Hebei, and Shanxi provinces. The soil in these dry areas contains a high proportion of sand, and strong winds can transport these sand particles for 3,000 km or even further. The deserts of Gansu Province and Xinjiang Uygur Autonomous Region, which are thousands of miles away, may also be the source of dust storms in Beijing (Pan & Liu 2011).

Sandstorms are frequent in northern China, especially in Inner Mongolia, which experiences some 20 days of sandstorms a year, particularly during the spring. However, they have an impact well beyond the drylands. For example, on 5 May 1993, a catastrophic dust and sandstorm affected 12 million people in 72 counties across 4 provinces. In total, a 40 million ha area was affected, with casualties of one hundred people and thousands of livestock (Liu & Diamond 2005).

The continuity of drought in winter and spring as well as the damages to ground vegetation have led to the growing deterioration of the environment. However, dust storms not only damage the quality of the environment, they also have negative impacts on health. Many studies have shown a significant correlation between dust events and respiratory and cardiovascular hospitalizations after adjusting for the effects of SO2 and/or NO2 exposure (Pan & Liu 2011). Furthermore, scientists have found that dust clouds were possible transmitters of influenza, SARS, and hand, foot, and mouth disease (HFMD), among others (Vidal 2009).

3.5 Floods and landslides

The Yellow River, known as the Huang He in China, supplies water to 155 million people (about 12% of China's population), and irrigates 7.3 million ha (about 15% of China's farmland). More than 400 million people live in the Yellow River basin, and the river is vital for their sustenance (Wang et al. 2015). The Yellow River, is slow and sluggish along most of its course. Yet, it is also one of the wildest and most destructive rivers in the world. Since historians began keeping records in 602 B.C., the river has changed its course 26 times and produced 1,500 floods that have killed millions of people. The root of these disasters is the large amount of silt generated by soil erosion. The Yellow River discharges three times the amount of sediment of the Mississippi River, and some regard it as the world's muddiest major river. 1.5 billion tons of silt is washed into the Yellow River every year, and the vast amount of sediment sometimes makes the water look like chocolate milk. Three quarters of this sediment is carried down to the Yellow Sea, and the rest is deposited in the river beds, causing the water level to rise (Wang et al. 2015). According to Mofcom

(2009), the silt deposited on the riverbed makes it rise on average 10 cm each year. The result is that the riverbed of many downstream sections of the river is 3 to 5 meters higher than the surrounding land. The "hanging-riverway" situation can result in flooding disasters if the dikes breach (Luo et al. 1997; Liu et al. 2014). As a consequence, soil erosion causes an increase in flooding, not only because the vegetation that once captured rainwater and slowed its flow into the rivers is gone, but also because of the rise of the river bed (Wang et al. 2015).

The water running off the hillsides also intensifies peak river flows, resulting in the erosion of riverbanks and increasing the risk of natural landslides. In addition, the more soil is washed into the river, the less of it remains on the land for farmers to use (Ford 2011). According to Huang and Li (2011), rainfall and earthquakes are the primary trigger factors of landslides. However, human activities, including construction, tree cutting, and farming also contribute to the instability of mountain slopes, which has become the primary cause for the catastrophic landslides that occur in China.

3.6 Accumulation of silt in dams

China has built more than half of the large reservoirs in the world since 1950, mainly for the production of hydroelectricity (Gao et al. 2015). When the silt contained in the rivers reaches the reservoir, it sinks and settles behind the dam. The more sediment a river carries, the faster the silt will accumulate. As the sediment builds up at the bottom of the reservoir, the dam slowly loses its water storage capacity and its original functions, in particular its electricity generation capacity (Wang et al. 2013). Besides filling the reservoirs, the large amounts of sediment also damage the structure and components of dams. The erosion and cracking of the tips of turbine blades by water-borne sand and silt considerably reduces their generating efficiency and often requires expensive repairs. Unfortunately, there is no safe and economic way to remove the sediment from behind the dams (Wang et al. 2013).

The speed of reservoir sedimentation is dependent on the size of the reservoir and the amount of sediment flowing into it: a small reservoir on an extremely muddy river will rapidly lose capacity, while a large reservoir on a very clear river may take centuries to lose an appreciable amount of storage. According to Wang et al. (2005), the average rate of storage capacity loss in the US is around 0.2% per year, with regional variations ranging from 0.5% per year in the Pacific states to just 0.1% in reservoirs in the American north-east. World-wide, the annual average rate of storage loss due to reservoir sedimentation is estimated to be between 0.5 and 1% of the total storage capacity (Wang et al. 2005). Major reservoirs in China lose their capacity at an annual rate of 2.3%, over ten times faster than the US average (Wang et al. 2013).

The Three Gorges Dam on the Yangtze River in China was specifically designed for the purpose of managing sedimentation. Carefully scheduled discharges were supposed to eliminate the backlog of sediment over the next 100-150 years. However, a 2013 report revealed that two-thirds of all river sediments are still blocked behind the dam every year (Wang et al. 2013). Engineers of the Three Gorges Dam predict that by the 2020s, the sedimentation of the Yangtze River could start causing problems upstream in the city of Chongqing. Fan Xiao, a Sichuan Province geologist and a critic of the Three Gorges Project, along with other scientists, claim that due to the rate of sediment accumulation, Chongqing could experience flooding and shipping issues much sooner than that (Yardley 2007).

According to LADA (2010:53), since 1981, 29 small-sized reservoirs in Yulin and Yan'an of northern Shaanxi Province, with a total capacity of 62 million m3, have been completely filled up by silt. There are many more examples of reservoirs that have lost at least some of their holding capacity due to siltation (LADA 2010):

- The Sanmenxia Reservoir in the Yellow River basin was completed in 1960, and by October 1964 it had accumulated 3,750 million m3 of sediment deposits, corresponding to a 62.9% loss of the storage capacity.

- The Shenmuwaluo Reservoir, built in 1977, with a storage capacity of 6.26 million m3, was fully silted up by 1988.

- The Liujiaxia reservoir, built in 1968, accumulated 1.2 billion m3 of silt by 1991.

Table 3 shows the sedimentation in the major reservoirs on the Yellow River basin from the 1960s onward to 2000. In total, 13.42 Gt of sediment had been trapped in the 15 reservoirs of the Yellow River basin by 2000. For the 601 reservoirs with a storage capacity over 1 million m3 in the Yellow River basin, the amount of deposited sediment in the backwater zones was estimated at 10.9 billion m3 in 1989, which accounted for 21% of the total storage capacity at the time (Ran et al. 2013).

Table 3 Sedimentation of major reservoirs in the Yellow River basin

Reservoir name	Initial storage capacity (km^3)	Filled sediment (gt)	Time period
Sanmenxia	9.75	8.908	1960—1997
Liujiaxia	5.70	1.833	1968—2000
Longyangxia	24.70	0.277	1986—2000
Qingtongxia	0.62	0.736	1967—2000
Yanguoxia	0.22	0.240	1962—2000
Tianqiao	0.07	0.076	1977—2000
Wangyao	0.20	0.134	1978—2000
Wanjiazhai	0.90	0.078	1997—2000
Bapanxia	0.05	0.038	1970—2000
Bajiazhui	0.53	0.420	1961—2000
Fengjiashan	0.39	0.110	1974—2000
Fenhe	0.70	0.472	1961—2000
Sanshenggong	0.08	0.056	1960—2000
Taoqupo	0.06	0.019	1979—1995
Yangmaowan	0.12	0.023	1973—1995
Total	44.08	13.420	

Source: Ran et al. (2013)

Dams can be equipped to flush out the silt. One dam with such facilities is the Xiaolangdi Dam, China's second largest dam facility after the Three Gorges Dam. The dam is used to control flood, reduce silt, produce electricity, and facilitate irrigation, among others (LADA 2010). The Loess Plateau deposits 1.6 billion tons of silt into the Yellow River annually, and one of the primary functions of the earthen dam is to prevent the river from rising, by storing the silt. During the rainy season, the reservoir holds the water, acting as a buffer against floods. During the dry season, the water is used for irrigation. In addition, during the dry season, the accumulated silt is flushed out through three specialized holes (Xia et al. 2016). As much as 30 million tons of silt are let out every year from the dam's reservoir. The operation lowers the river bed in the lower reach of the river by an average of 2 meters (Wang et al. 2015). However, the reservoir of the Xiaolangdi Dam has the capacity to store water only until 2020. At that point, it will no longer be possible to release the water and flush out the sediment from the reservoir, and the river levels will once again start to rise.

4 Conclusions

This paper reviewed the literature on the direct and indirect consequences of soil degradation. Soil degradation processes consist mainly of soil acidification, salinification, and desertification, and result in the loss of nutrients and a substantial reduction of crop yields. Soil degradation occurs mainly in the arid north and the mountainous areas in the west, where it has direct environmental (such as landslides and flooding) and economic (such as lower incomes from farming and livestock raising) impacts. However, it also has important nation-wide impacts, including dust storms, floods, and the siltation of dams. Furthermore, there is a growing risk that a reduction in grain and livestock output may raise the price of food beyond what is socially acceptable.

Soil degradation is the outcome of various natural factors and human activities that result from people's inadequate use of land resources and the *"grow first, clean up later"* attitude prevalent in China (Currell 2013). However, the root causes of soil erosion can be traced back to politics (legal constraints to the ownership of the land, which discourage farmers to invest in reducing erosion), economics (lack of funds to invest in land conservation, or too low incomes or savings for farmers to set aside land for a period of time and forsake income for that period), demography (population growth that compromises the ability to use resources sustainably) (Blaikie 1985), or a urban-rural planning bias (in China, as well as in other countries, such as Thailand (Warr 2001), high taxes for agricultural products were used to generate funds to industrialise the country (Oi 1993), which in turn amplifies the economic causes of soil erosion).

However, the government has been doing much to address the problem. Demographic factors have virtually disappeared, as economic growth and the Grain for Green have made many rural dwellers migrate to cities (Delang and Yuan 2014); China gradually cut the agricultural land tax, and by 2006 abolished it (Wang and Shen 2014); the excessive use, and low quality, of fertilisers is being addressed through field trial-based extension work that results in enhanced management practices (Cui et al. 2018); land ownership and usufruct laws are being reformed, even though the government's communist ideology makes this somehow complicated (Ye, 2015). To address soil degradation, the government has undertaken a number of measures, in particular reforestation and vegetation restoration programs in the most degraded – and least agriculturally productive – areas. In spite of those efforts, the process of restoration is difficult, time consuming, and very expensive, since soil erosion in China covers very large areas with various types of climates, landforms, soils, and vegetations, with significant variations in natural conditions, social conditions, and economic activities.

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