A PERSPECTIVE ON WATER RESOURCES IN CHINA: INTERACTIONS BETWEEN CLIMATE CHANGE AND SOIL DEGRADATION

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Abstract. Water is one of the most critical resources in China. Climate change and soil degradation will be two major, interrelated environmental challenges faced by managers of water resources in coming decades. In this study, we used a water-balance model and updated databases to assess the interacting impacts of climate change and soil degradation on China's future water resources. We plotted the spatial pattern of changes in actual and potential evapotranspiration, soil moisture deficits, and surface runoff across China in the 2020s using a resolution of 0.5° latitude and longitude under scenarios based on climate change, soil degradation, and a combination of the two. The results showed that climate change would affect the magnitude and spatial pattern of water resources on a national scale. Some regions in central, southwestern, and northeastern China would become more vulnerable to disastrous drought and floods as a result of soil degradation. Under the combined impacts of climate change and soil degradation, soil moisture deficits would increase most in central, western, and southwestern China; surface runoff would increase most in southeastern China. More detailed process-based models are needed to capture feedback mechanisms more effectively.

1. Introduction

Water resources play a vital role in forestry, agriculture, fisheries, livestock production, and industrial activity in China. However, these resources are also likely to be highly sensitive to climate change and human activities (IPCC, 1998). Climate change and soil degradation are two major, interrelated global environmental challenges that managers of China's water resources will face in the coming decades (Varies and Vakkilainen, 2001). Climatic change could have a major impact on the hydrologic cycle and, consequently, on the available water resources, the potential for floods and drought, and agricultural productivity (Evans, 1996; Tao et al., 2003a). By changing the proportion of soil organic and mineral constituents and altering soil structure, soil degradation will usually decrease a soil's water-holding capacity, with a consequent increase in runoff and the magnitude of nutrient and water stress (e.g., Mabbutt, 1989; Nicholson, 1989; Bryant et al., 1990; Williams and Balling, 1996). Erosion-induced loss of water-holding capacity has been recognized as the most common cause of productivity decline in most environments (Williams et al., 1981; Pierce and Lal, 1994; Oropeza-Mota et al., 1995). In temperate Asia,

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large increases in surface runoff—leading to soil erosion and degradation, frequent waterlogging in the south, and spring drought in the north—will ultimately affect agricultural productivity (Arnell, 1999). Furthermore, the agricultural sector in arid and semi-arid Asia is potentially highly vulnerable to climate change because of expected degradation of the limited areas of arable land (IPCC, 2001).

Soil degradation is a serious problem in China. An investigation by the Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD; Lynden and Oldeman, 1997), revealed that more than 466 million ha (50% of the land) in China are affected by one or more types of soil degradation, 73 million ha of the total land area are affected by moderate degradation, and 86 million ha are experiencing severe soil degradation. Water-caused erosion affects 180 million ha in China, at least to some degree. Moreover, desertification-prone lands cover a total of 33 400 ha (Feng et al., 2001).

Interactions between climate change and soil degradation are believed to be a primary cause of the more frequent droughts, disastrous floods, and related environmental problems such as frequent dust storms that have been reported in China in recent years (Qian and Zhu, 2001). These issues are continuing to affect biological productivity and environmental sustainability. For planning and evaluating potential mitigation strategies, comprehensive assessments of the impacts of climate change and soil degradation on water resources are needed. Feddema (1999) introduced an effective methodology for simulating the future effects of human-induced soil degradation and climate change on African water resources. In the present study, we modified Feddema's methodology and used updated datasets to assess the impacts of climate change, soil degradation, and their interaction on the future of China's water resources.

2. Methods and Data

We ran a daily water-balance model under four experimental conditions: (1) baseline climate and soil conditions, (2) climate change, (3) soil degradation, and (4) climate change combined with soil degradation. Changes in the water resources and in the potential for drought or floods caused by climate change or soil degradation were evaluated by comparing the resultant components of the water cycle under corresponding conditions.

2.1. WATER-BALANCE MODEL

The water-balance model developed by Willmott et al. (1985) and improved by Tao et al. (2003a) was used in the present study. This model accounts for most components of the water cycle and is well established (Tao et al., 2003a). Potential evapotranspiration was calculated using the Penman-Monteith method (FAO, 1992), but we used Chang's (1970) method to calculate net radiation because it is more accurate than the empirical formulas developed by Penman (1948) and Budyko (1956).

2.2. DATA SOURCES

The water-balance model requires data on a soil's water-holding capacity plus monthly climatic data, including precipitation, mean temperature, radiation, vapor pressure, and wind speed. For soil water-holding capacity, we used the plant-extractable capacities developed by Dunne and Willmott (1996) as the baseline condition for global grid cells of 0.5° latitude and longitude. We modified these data slightly by assigning a water-holding capacity of 5 mm for the soil of unvegetated areas, where no value was assigned originally. The soil's water-holding capacity under future degraded soil conditions was simulated by modifying the baseline condition using a soil degradation scenario. We obtained monthly climatic data for the 1961–1990 period from surface climatology data recorded by the Climate Research Unit (CRU) of the University of East Anglia (Norwich, UK) for grid cells of 0.5° latitude and longitude (New et al., 1999). Compared with the climatologies developed by Legates and Willmott (1990a, b; "L&W climatologies" hereafter), the CRU climatologies tended to have a poor spatial sampling intensity, particularly in some of the more remote regions of the Earth, including the Himalayas and portions of interior China. Large errors in water-balance output could sometimes be produced by the combination of sampling issues and problems with extrapolation and interpolation (Legates and Mather, 1992). However, humidity data was only available from CRU, and this data was required to calculate potential evapotranspiration (PET) in the Penman-Monteith method. The trade-off between poor spatial sampling intensity and an improved PET model will be discussed later in this paper.

2.3. SCENARIO DEVELOPMENT

2.3.1. *Climate Change*

Simulated changes (differences in temperature and in the ratios of other variables) in our climatology, simulated using the general circulation model (GCM) for the 2021–2030 and 1961–1990 periods, were combined with CRU's mean monthly climatology data (1961–1990) to develop climate-change scenarios for the 2021–2030 period using a grid with 0.5° resolution for latitude and longitude (Tao et al., 2003a). We used the HadCM2 GCM experiment conducted by the Hadley Centre (Exeter, UK), with integration of the effects of greenhouse gases plus sulfates and a 1% compound increase (http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html).

2.3.2. *Soil Degradation*

We used the ASSOD, developed by the United Nations Environment Programme (UNEP) and the International Soil Reference and Information Center (ISRIC), as our basis for developing future soil degradation scenarios in the study (Lynden and Oldeman, 1997). ASSOD is a sequel to the Global Assessment of the Status of Human-Induced Soil Degradation (GLASOD) survey (Oldeman et al., 1991), and it developed a small-scale (1:5 000 000) map of soil degradation in South and Southeast Asia, based on a modified and refined GLASOD methodology. ASSOD evaluated more recent states of soil degradation (from about 1981 to 1995), and the results provided much greater detail than those of GLASOD.

The ASSOD project classified soil degradation using six major parameters:

1. *Type* of soil degradation (such as water erosion, chemical deterioration).
2. *Degree* of degradation, expressed as the impact on productivity (five classes from negligible to extreme).
3. *Extent* of soil degradation, expressed as a percentage of the mapping area affected.
4. *Rate* of soil degradation, ranging from +3 (rapidly increasing) to −3 (rapidly decreasing).
5. *Causative factors* (five classes: agricultural activities, deforestation and removal of natural vegetation, over-exploitation of vegetation for domestic use, overgrazing and industrial activities).
6. *Rehabilitation* or *protective measures* (four classes: plant management (vegetative) practices, land management practices, structural practices, and other practices).

In the present study, we converted the data to fit a 0.5° resolution latitude and longitude grid so that the data would be compatible with our other datasets. Our estimates of the impact of degradation on soil water-holding capacities (W^*) used a methodology similar to that employed by GLASOD to determine the overall severity of degradation (Oldeman, 1988; Middleton and Thomas, 1992), as described by Feddema (1999). Using sets of weighting functions to describe the impact of each type of degradation and quantitative measures of the degree and extent of degradation, we calculated an overall reduction factor (RF) for soil water-holding capacity for each area:

$$\mathrm{RF} = \sum_{i=1}^{2} (\mathrm{WF}_{\mathrm{cause}})_i (\mathrm{WF}_{\mathrm{degree}})_i (\mathrm{WF}_{\mathrm{extent}})_i, \tag{1}$$

where $\mathrm{WF}_{\mathrm{cause}}$ represents a numerical weighting factor assigned to the type (cause) of the soil degradation at a location, $\mathrm{WF}_{\mathrm{degree}}$ represents a numerical weighting factor assigned to the observed degree (seriousness) of the soil degradation type, $\mathrm{WF}_{\mathrm{extent}}$ represents the numerical weighting factor assigned to the observed extent (area percentage) of the soil degradation type, and the subscript i represents the primary ($i = 1$) and secondary ($i = 2$) types of soil degradation.

Among the soil degradation types identified in ASSOD, only those considered to have a direct impact on soil water-holding capacity were assigned weights to represent their relative impact; a weighting factor of 0.00 was assigned to all other

TABLE I
Types of soil degradation from the ASSOD study and their weighting factors in the present study[a]

Type of soil degradation	Weighting factor
Water erosion	
Wt: loss of topsoil by means of sheet erosion or surface wash	1.00
Wd: terrain deformation	0.75
Wo: off-site effects of water erosion in upstream areas	0.00
Wind erosion	
Et: loss of topsoil due to wind action	1.00
Ed: terrain deformation	0.75
Eo: off-site effects of wind erosion	−0.50
Chemical deterioration	
Cn: fertility decline and reduced organic matter content	0.00
Cs: salinization or alkalinization	0.00
Cp: *pollution*	0.00
Ct *: dystrification*	0.00
Ce *: eutrophication*	0.00
Physical deterioration	
Pc *: compaction*	1.00
Pk *: sealing and crusting*	1.00
Ps *: lowering of the soil surface*	1.00
Pa: aridification	1.00
Pw: waterlogging	0.00
Pu *: loss of productive function*	0.00
Others	
Sn: Stable under natural conditions	0.00
Sh: Stable under human influence	0.00
W: Wasteland	0.00

[a]Types that did not occur in the study area are presented in italics.

types (Table I). For each type of soil degradation in the areas examined, the ASSOD database also provided information on the degree, impact, and rate of change of the degradation. We used the same weighting schemes used by GLASOD (Oldeman, 1988; Oldeman et al., 1991) and by the World Desertification Atlas (Middleton and Thomas, 1992) to quantitatively assess the degree and extent of degradation associated with a specific type of degradation. The weighting schemes used to represent the extent of degradation are shown in Table II; those used to assess the degree of degradation are shown in Table III.

The primary and secondary types of degradation in China and their extents, impacts, and rates, are illustrated in Figures 1 and 2, respectively. The primary type of

TABLE II
Extent of soil degradation from the ASSOD database and their weighting factors in the present study

Extent category	Area affected	Weighting factor
Infrequent	0–5	0.025
Common	5–10	0.075
Frequent	10–25	0.175
Very frequent	25–50	0.375
Dominant	>50	0.750

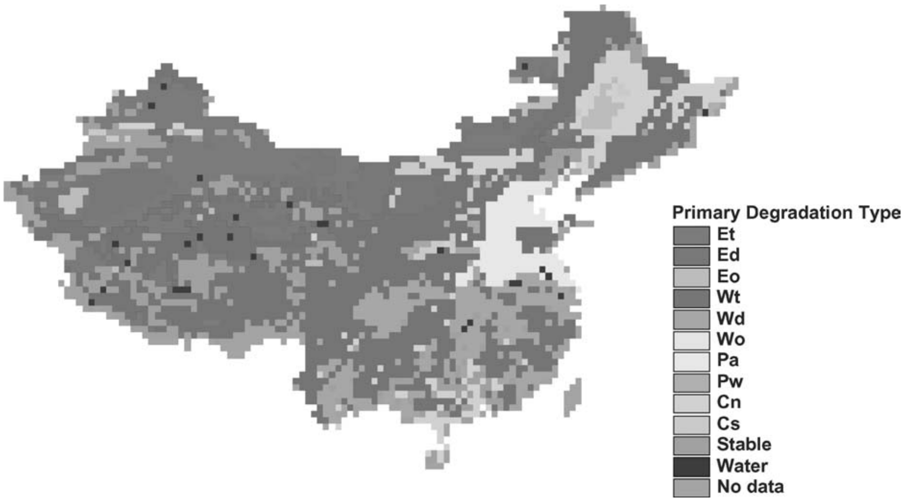
TABLE III
Degrees of soil degradation from the ASSOD database and their weighting factors in the present study

Degree categories	Weighting factor
None	0.00
Light	0.25
Moderate	0.50
Strong	0.75
Extreme	1.00

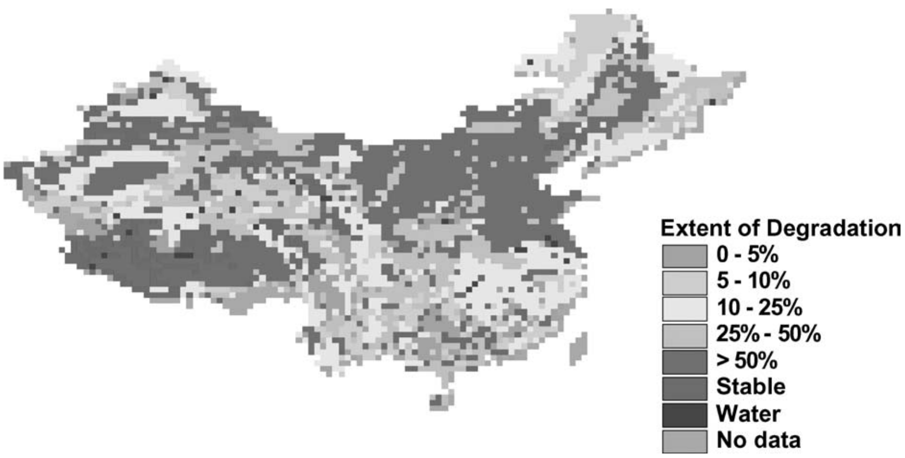
degradation in northern and northwestern China is wind erosion due to overgrazing. In the southern and southwestern parts of China, and in part of northeastern China, water erosion is the primary type of degradation and results from deforestation or overexploitation of natural vegetation. About half of the area of China represents land with degradation extents greater than 10%, and the extent of the degradation reaches more than 50% in quite a few areas, especially at the fringes of deserts. This degradation has strong impacts on soil productivity in northern, northwestern, and southwestern China. Degradation is increasing slowly in most of China, but is decreasing slowly in southeastern China (Figure 1).

The secondary types of degradation are also dominated by wind- and water-caused erosion. These types have a relatively large extent in central, southwestern, and northeastern China and have strong impacts on soil productivity in southwestern and northwestern China. Degradation as a result of secondary causes is generally increasing slowly, but is decreasing slowly in parts of southeastern China (Figure 2).

We developed a future scenario for soil degradation based on extrapolation of the ASSOD survey. To do so, we assumed that the primary and secondary causes of degradation would remain the same as those assigned in the ASSOD database. Both the extent and degree were assumed to increase or decrease by one, two, or three categories by the start of the 2021–2030 period (about 30 years after the ASSOD study) when the degradation rates were changing (respectively) slowly, moderately, or rapidly. Both the extent and degree were assumed to remain at their present levels when the degradation rate was zero (no change). In the future scenario, the extent and impact of soil degradation were limited to the corresponding ASSOD-defined categories. The projected extent and impact for the primary and secondary types of degradation, representing predicted future soil degradation for the 2021–2030 period, are shown in Figures 3 and 4.



(a)



(b)

Figure 1. Primary causes of degradation and their attributes: (a) primary type of degradation; (b) extent (area percentage) of degradation; (c) impact of degradation; (d) rate of degradation. Explanations of the degradation types appear in Table I.

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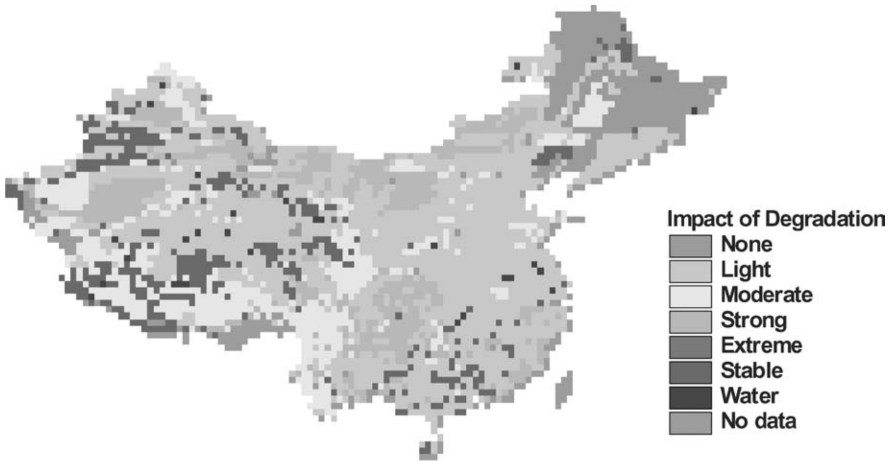

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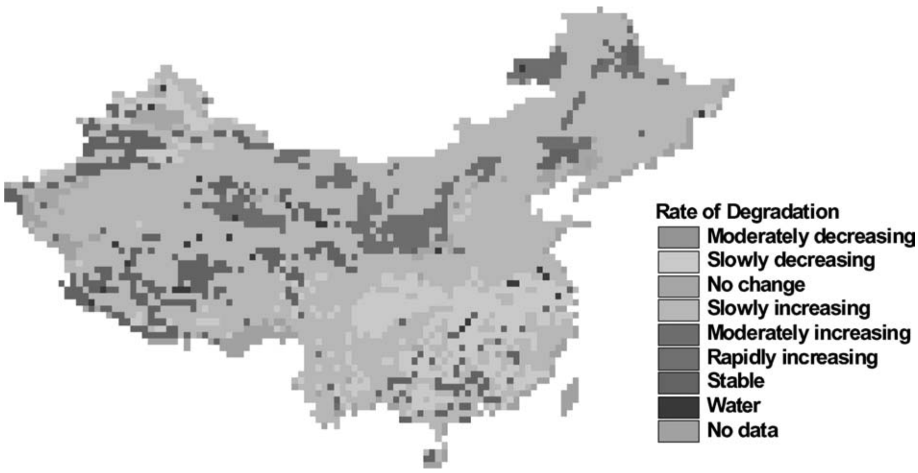

(d)

Figure 1. (*Continued*)

To simulate the impacts of soil degradation on soil water-holding capacity, we calculated reduction factors for the primary and secondary causes of degradation (RF1 and RF2, respectively). The sum of RF1 and RF2 provides an estimate of total RF for a location. We simulated the soil's water-holding capacity after degradation by multiplying (1.0 – RF) by the soil's original water-holding capacity, as developed by Dunne and Willmott (1996).

Figure 5a shows the soil water-holding capacity based on Dunne and Willmott (1996), which is considered to represent the capacity before human disturbance. Figure 5c shows the predicted reduction factor for soil water-holding capacity based on the predicted soil degradation for the 2021–2030 period. For the sake of comparison, the reduction factor for soil water-holding capacity based on present soil degradation (ASSOD survey) appears in Figure 5b. The reduction factor for soil water-holding capacity varies spatially and temporally as a function of the type, extent, impact, and rate of soil degradation. Desert areas and their fringes in northern China were affected most, and their condition is projected to become worse in the future. In southeastern China, the reduction factor is projected to decrease in the future because soil degradation is slowly improving in this region.

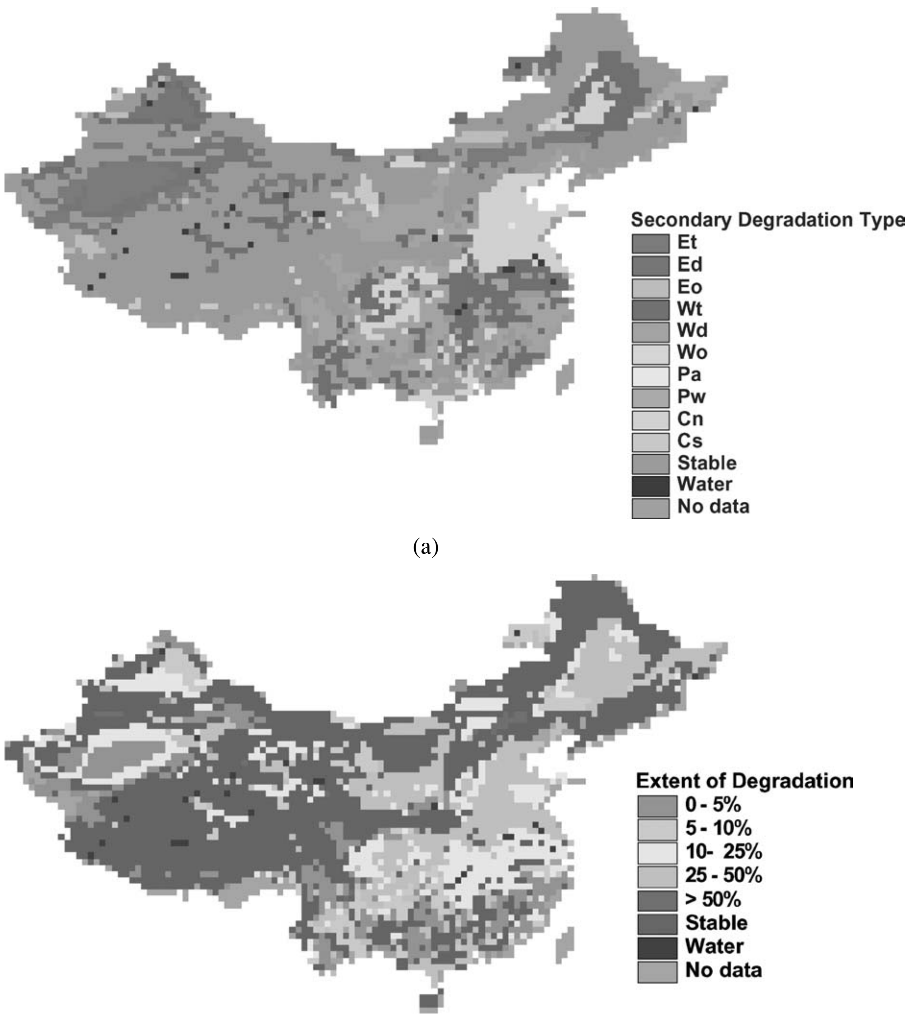

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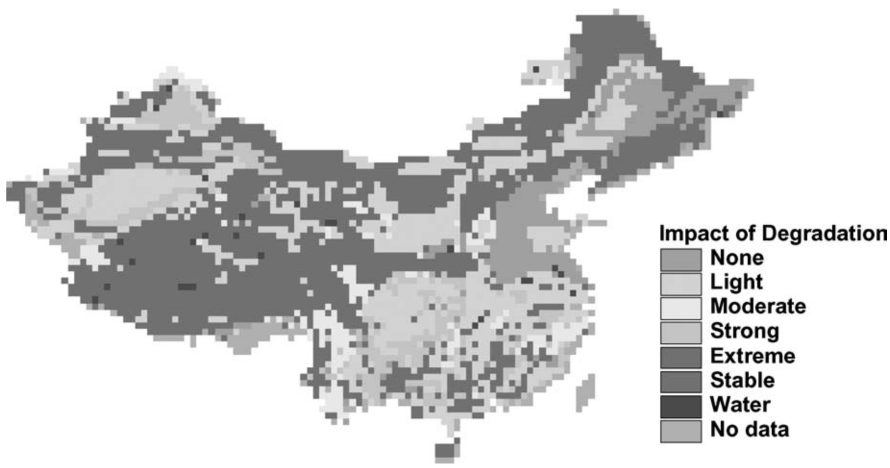
Figure 2. Secondary causes of degradation and their attributes: (a) type of degradation; (b) extent (area percentage) of degradation; (c) impact of degradation; (d) rate of degradation. Explanations of the degradation types appear in Table I. (*Continued on next page*)



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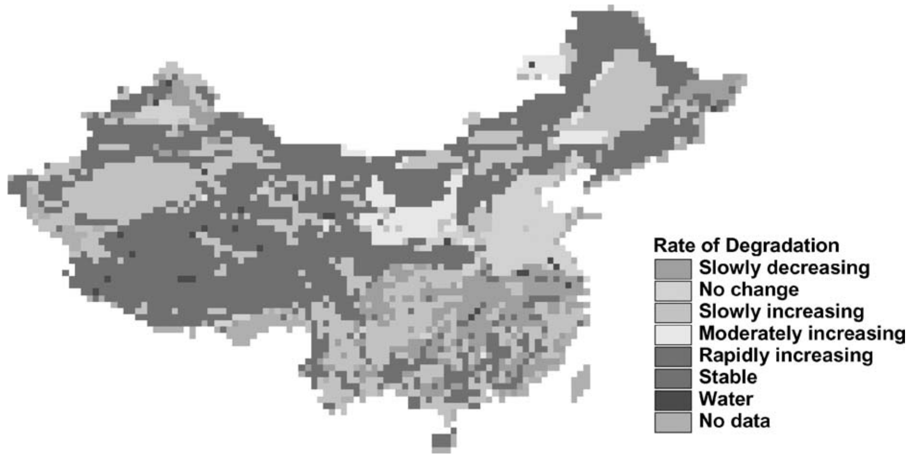

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Figure 2. (*Continued*)

2.4. EXPERIMENTS

We ran the water-balance model under four different experimental conditions to test the potential impacts of climate change, soil degradation, and a combination of the two factors on the water cycle.

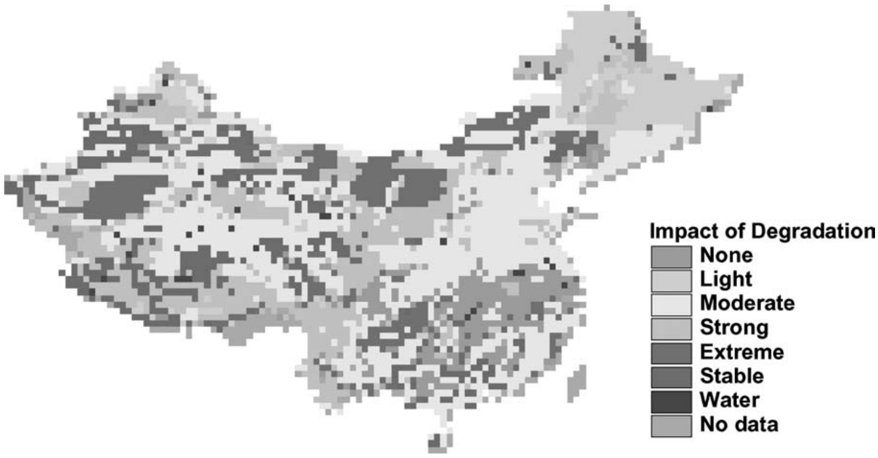
2.4.1. *Experiment I: Control*

To simulate baseline climatic conditions and the original soil water-holding capacities, we ran the water-balance model using the CRU climatology data for the 1961–1990 period and the soil water-holding capacities developed by Dunne and Willmott (1996).

2.4.2. *Experiment II: Climate Change*
To simulate the impacts of climate change, we ran the water-balance model using the climate change scenario for the 2021–2030 period and the soil water-holding capacities developed by Dunne and Willmott (1996).

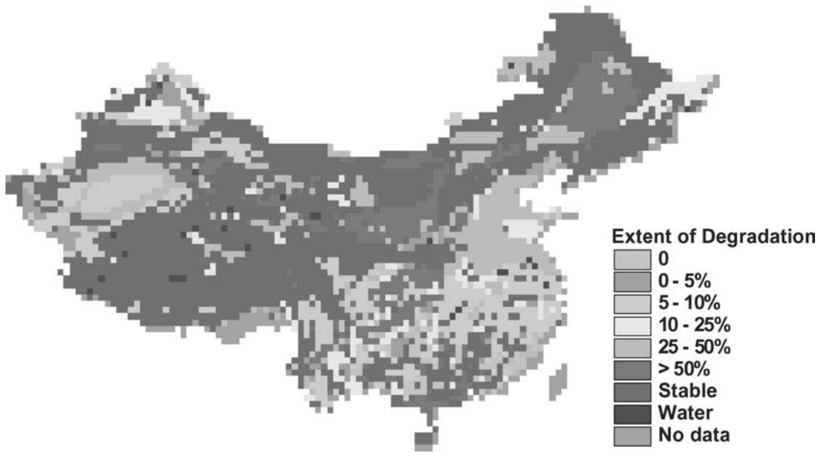
2.4.3. *Experiment III: Future Soil Degradation*
To simulate the impacts of soil degradation, we used Dunne and Willmott's (1996) soil water-holding capacities, modified by the predicted reduction factors for the 2021–2030 period and the CRU climatology data for 1961–1990.

(a)

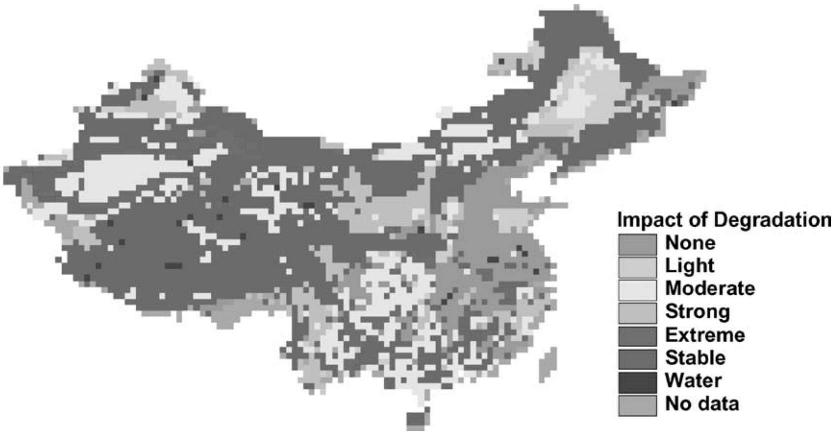


(b)

Figure 3. Predicted extents (a) and impacts (b) of the primary causes of degradation for the 2021–2030 period.



(a)



(b)

Figure 4. Predicted extents (a) and impacts (b) of the secondary causes of degradation for the 2021–2030 period.

2.4.4. *Experiment IV: Climate Change and Soil Degradation*

We simulated the combined impacts of climate change and soil degradation using the climate change scenario for the 2021–2030 period and Dunne and Willmott's (1996) soil water-holding capacities modified by the predicted reduction factors for 2021–2030.

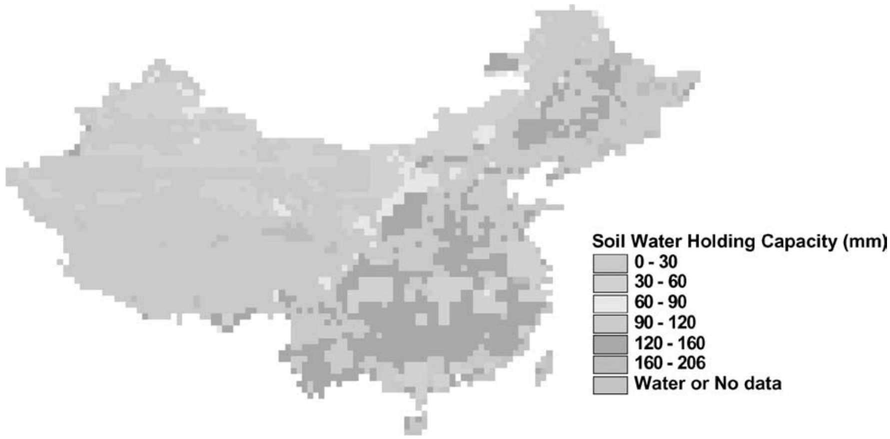
3. Results

3.1. TEMPERATURE

According to the CRU climatology data for the 1961–1990 period, the highest mean annual temperatures occurred in the tropical areas of southern China, whereas the coolest temperatures were found on the Tibetan Plateau (Figure 6a). According to the HadCM2 GCM, the mean annual temperature in the 2020s is projected to increase by 0.4–1.60 °C across China (Figure 6b). The most significant warming will occur in the northwest, whereas the lowest increase will occur in the southeast.

3.2. PRECIPITATION

According to the CRU climatology data for the 1961–1990 period, mean annual rainfall in China from 1961 to 1990 generally increased from northwest to southeast,



(a)

(b)

Figure 5. Soil water-holding capacity and its reduction factor as a result of soil degradation: (a) original soil water-holding capacity developed by Dunne and Willmott (1996); (b) reduction factor for soil water-holding capacity (RF) based on current soil degradation; (c) reduction factor for soil water-holding capacity (RF) based on the predicted soil degradation for the 2021–2030 period.

(*Continued on next page*)

(c)

Figure 5. (*Continued*)

ranging from less than 200 to more than 2200 mm per year (Figure 7a). When the HadCM2 GCM output is combined with the CRU data, changes in mean annual rainfall in the 2020s compared with precipitation levels during the 1961–1990 period exhibited high spatial variation. Precipitation is projected to increase the most (by more than 60 mm) in the northwest (Figure 7b), but is projected to remain constant or decrease by more than 30 mm in central and southwestern China. Increases in temperature and decreases in precipitation would lead to decreases in snow cover, particularly in the Tibetan Plateau and parts of northeastern China (Figures 7c and 7d).

3.3. POTENTIAL EVAPOTRANSPIRATION

Annual PET ranges from less than 350 mm to more than 1250 mm across China (Figure 8a). Values below 600 mm occur in northeastern China and the Tibetan Plateau, where annual mean temperatures are the lowest. Values above 900 mm are mainly found in northern China, particularly in the deserts of northwestern China, due to high radiation levels, high wind speeds, and low humidity (Figure 8a). The results agree well with those reported by the Global Agro-Ecological Zone program (Fischer et al., 2000). Nevertheless, PET estimation at the scale we used could be subject to a combination of sampling errors and extrapolation or interpolation problems in regions with poor spatial data distributions (see also, Tao et al., 2003b). For example, caution should be taken in explaining the very high PET values in northwestern China. The PET pattern calculated using FAO's Penman-Monteith method is not as similar to the temperature pattern compared to using the Thornthwaite approach (Thornthwaite, 1948; Feddema, 1999).

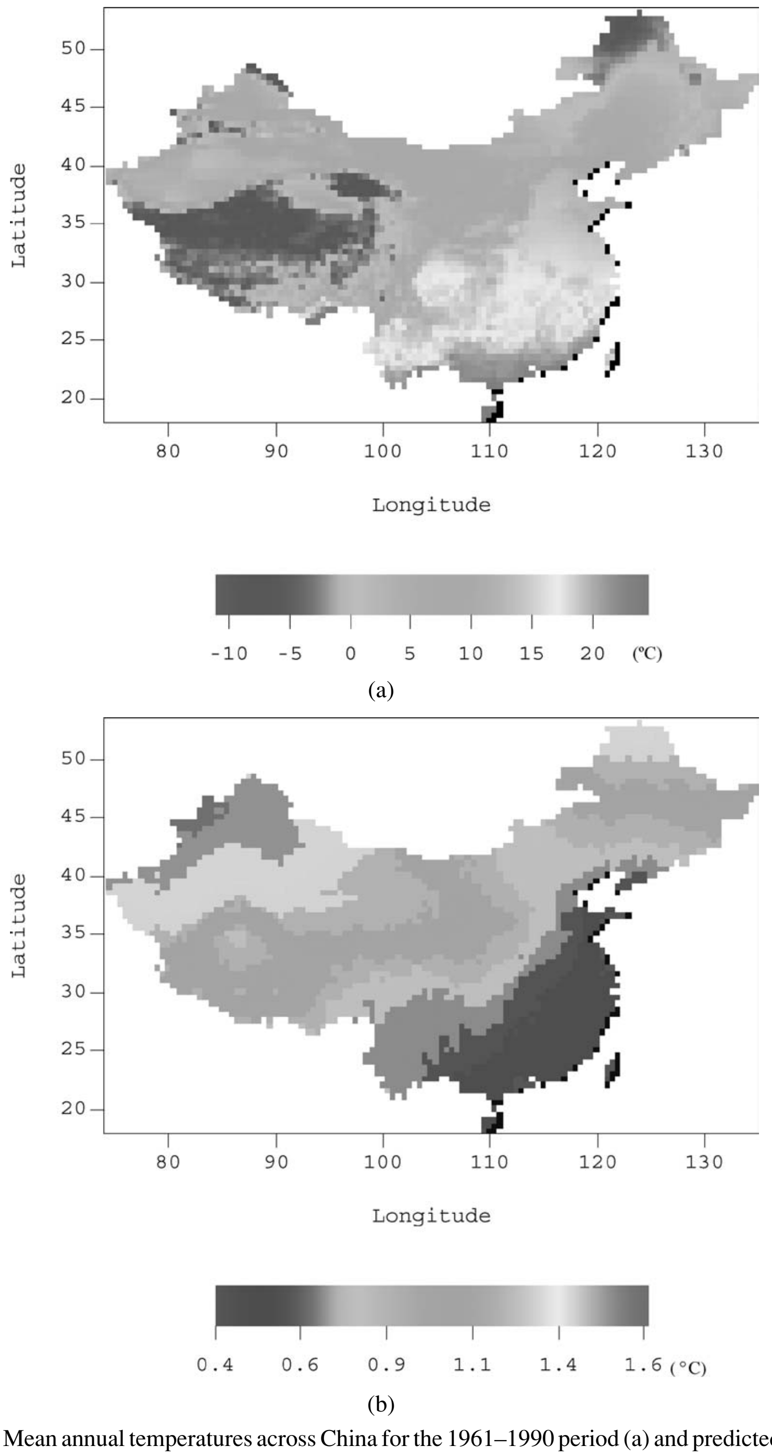
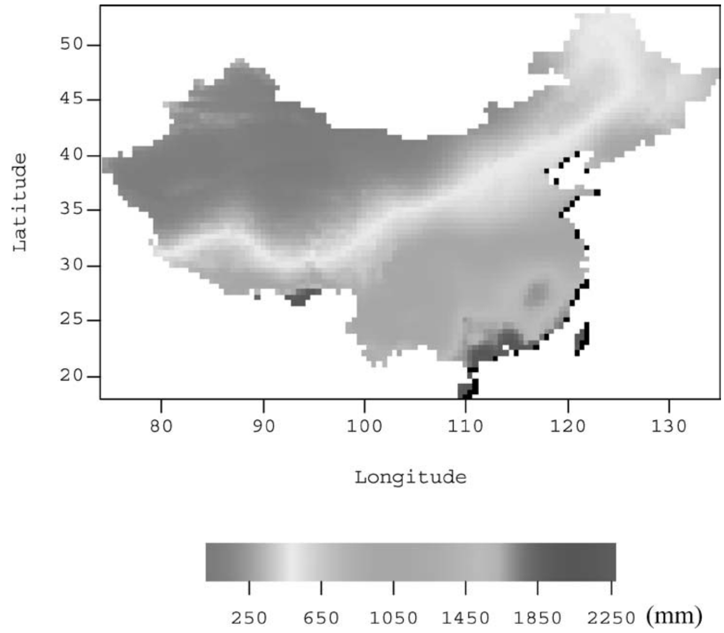
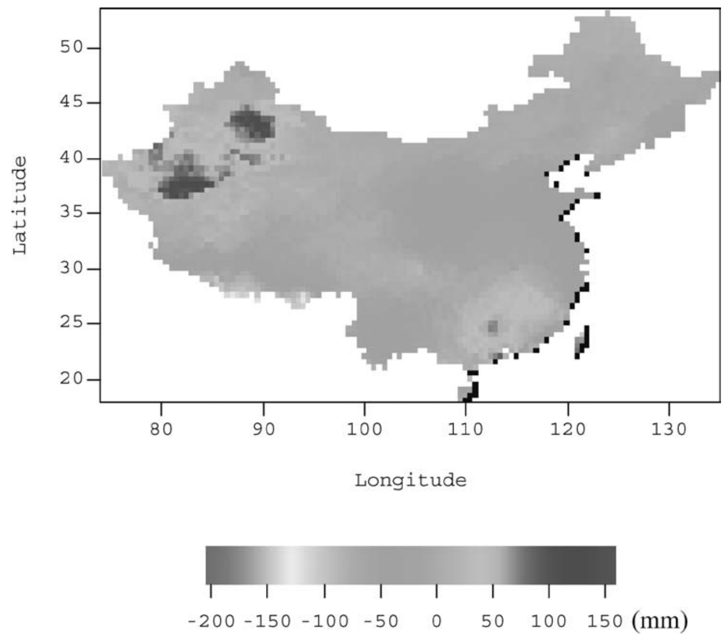


Figure 6. Mean annual temperatures across China for the 1961–1990 period (a) and predicted changes between the 2021–2030 and 1961–1990 periods (b).

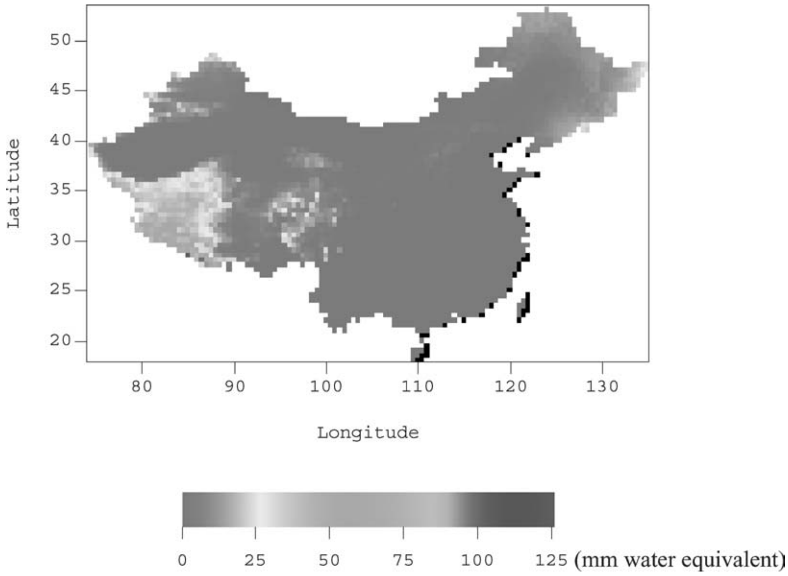


(a)



(b)

Figure 7. Mean annual total precipitation for the 1961–1990 period across China (a) and predicted changes in this parameter between the 2021–2030 and 1961–1990 periods (b); mean annual snow cover for the 1961–1990 period (c) and predicted changes in this parameter between the 2021–2030 and 1961–1990 periods (d). (*Continued on next page*)



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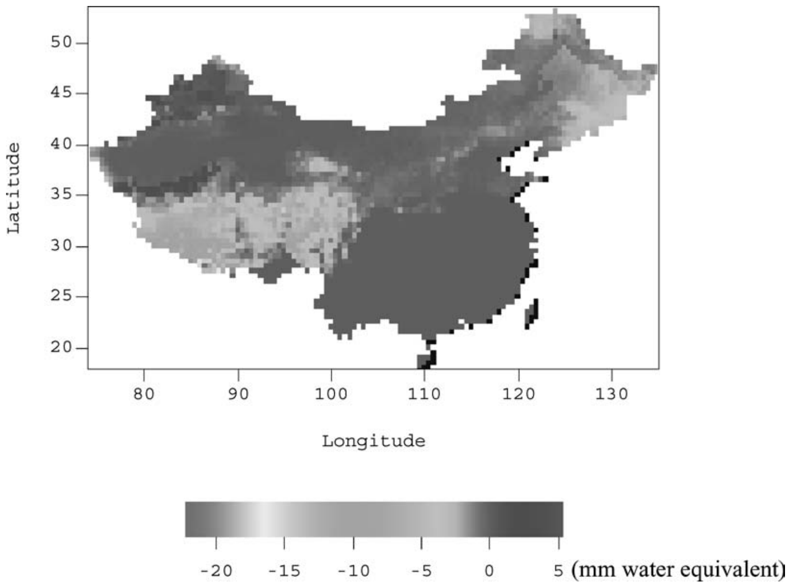
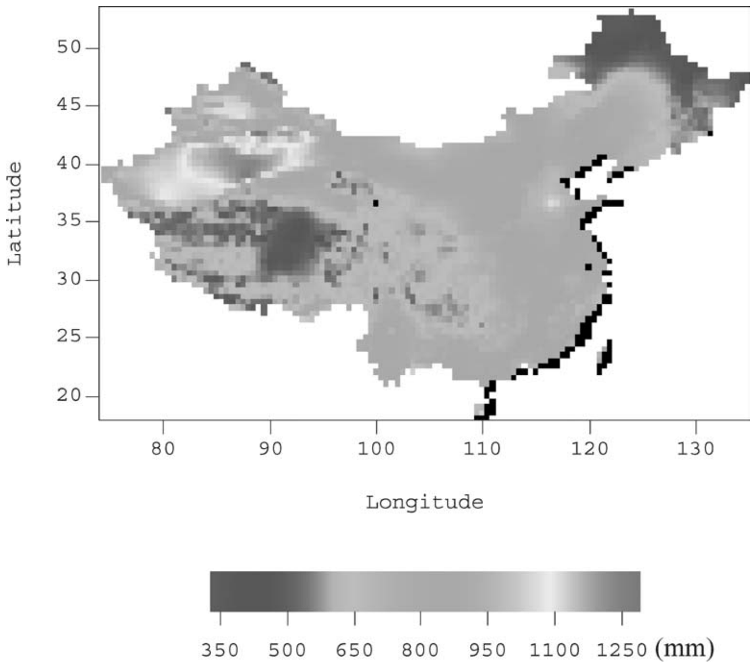


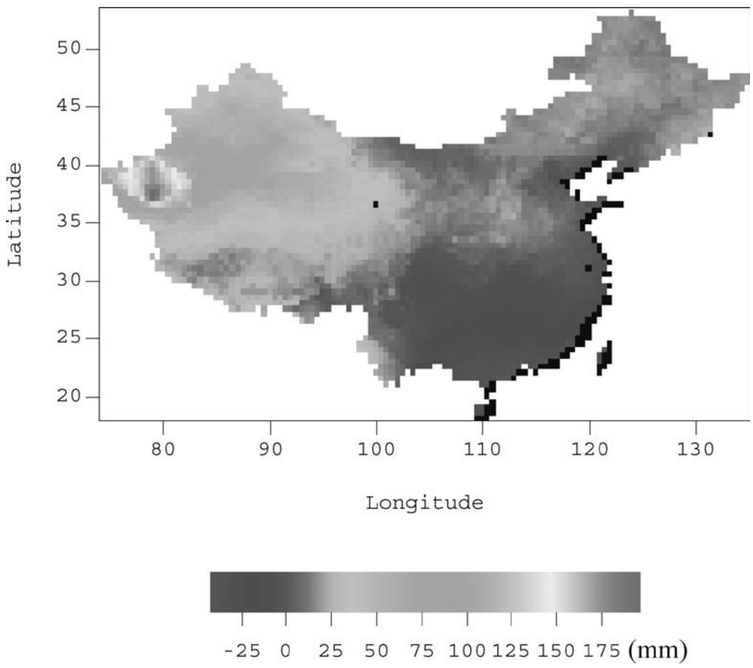
(d)

Figure 7. (*Continued*)

The climate change scenario based on the HadCM2 GCM results in a predicted decrease in water demand in southern and eastern China during the 2021–2030 period. In contrast, water demand is expected to increase in other regions, especially in the northwest (Figure 8b). The changes in PET are nonlinearly related to changes in radiation, temperature, wind speed, and vapor pressure.



(a)

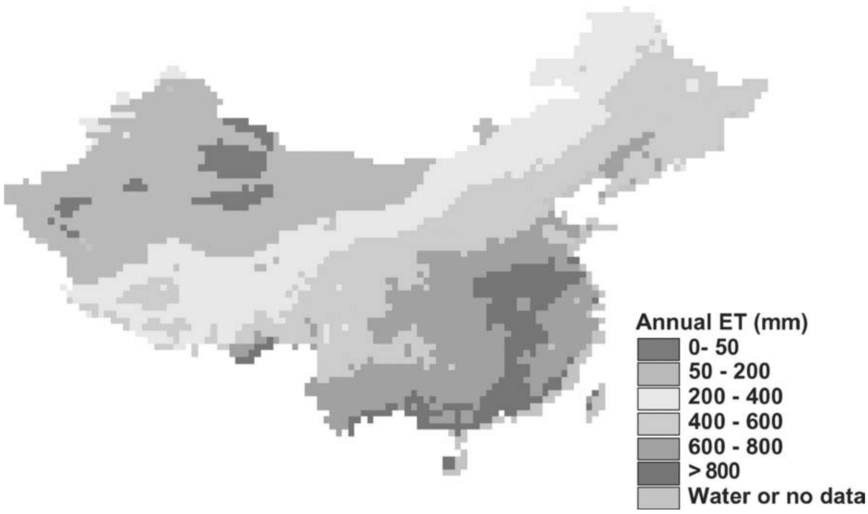


(b)

Figure 8. Mean annual potential evapotranspiration (PET) in China for the 1961–1990 period (a) and changes in this parameter between the 2021–2030 and 1961–1990 periods (b).

3.4. ACTUAL EVAPOTRANSPIRATION

Annual actual evapotranspiration (ET) generally increases from northwest to southeast, ranging from 0 mm to more than 800 mm (Figure 9a). The ET pattern is similar to that of precipitation (Figure 7a) because precipitation plays an important role



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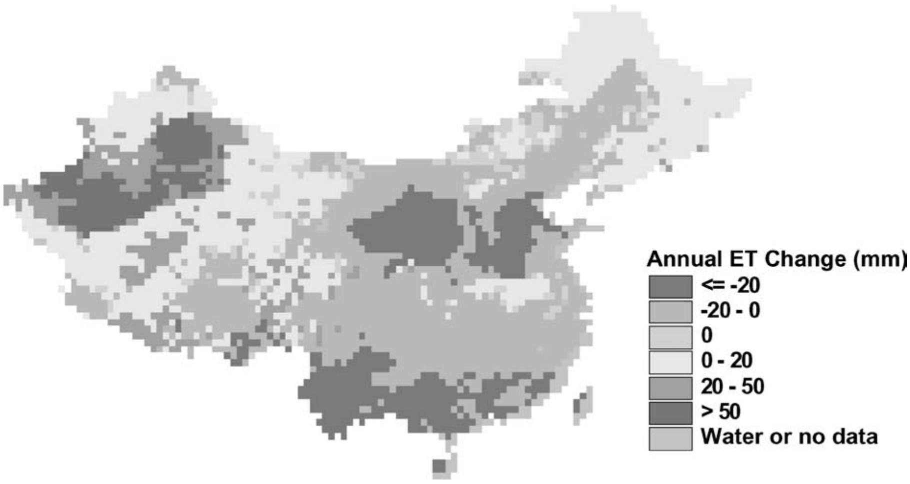
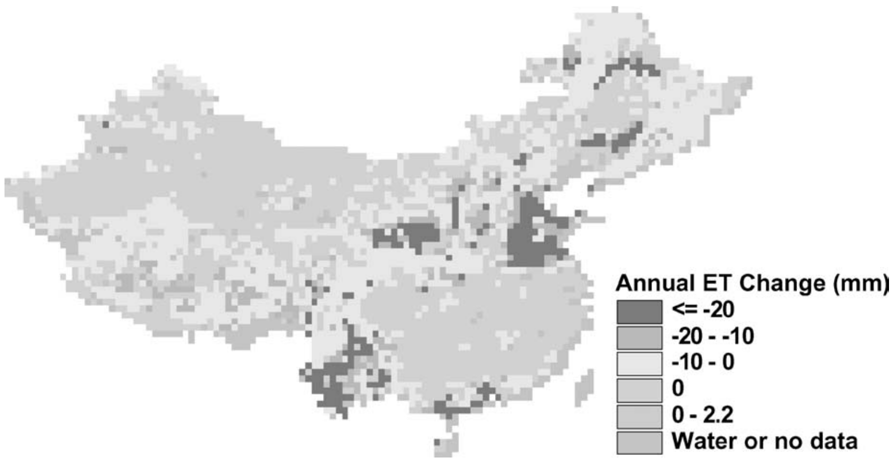


(b)

Figure 9. Mean annual actual evapotranspiration (ET) in China for the 1961–1990 period (a) and changes in this parameter between the 2021–2030 and 1961–1990 periods under three scenarios: climate change (b), soil degradation (c), and climate change combined with soil degradation (d). (*Continued on next page*)



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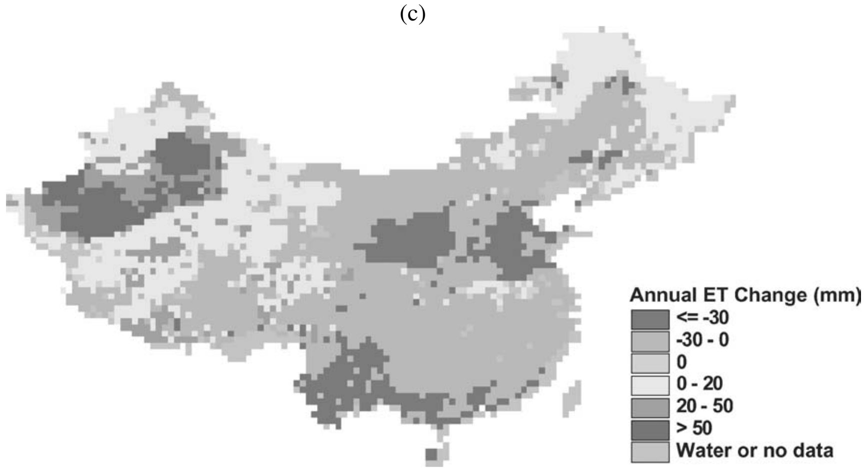


(d)

Figure 9. (*Continued*)

in ET, especially in the arid and semi-arid regions of northern and northwestern China.

Under the climate change scenario, ET is expected to increase in northeastern and particularly northwestern China (Figure 9b), where precipitation would increase. ET is expected to decrease or remain unchanged in other regions. In southeastern China, ET is expected to decrease even if precipitation increases because soil moisture is not the limiting factor for ET in the region.

ET is also affected by changes in the soil's water-holding capacity resulting from soil degradation (Figure 9c). In general, ET would decrease by from 0 to 10 mm across China in response to reduced soil water-holding capacities as a result of soil degradation. The amount of ET change depends on both the degree of reduction in soil water-holding capacity and on soil water content. For example, the region with the most severe reduction in soil water-holding capacity will be the desert areas in northern China (Figure 5c); however, the regions with the largest decreases in ET will be in central and southwestern China.

Under the combined impacts of soil degradation and climate change in northwestern and northeastern China, ET will increase because climate change will offset decreases caused by soil degradation (Figure 9d). However, in regions such as central and southwestern China, including the southern edge of the Tibetan Plateau, the impacts of climate change and soil degradation on ET will be additive. The combined impact will decrease ET by more than 30 mm in places.

3.5. SOIL MOISTURE DEFICIT

Soil moisture deficit is calculated as the difference between PET and ET and represents the shortage of water at a location. At present, the most severe moisture deficits are found in the north, particularly in the desert areas of northwestern China (Figure 10a), where high PET, low precipitation, and consequently low ET are found. In southeastern China, there is no or little soil moisture deficit.

Under the climate change scenario, soil moisture deficit may remain at or near 0 mm or may decrease by less than 20 mm in southeastern China (Figure 10b). In contrast, some areas of northwestern China would experience decreases in soil moisture deficit of around 20 mm because of increased precipitation. In other regions, soil moisture deficit is expected to increase as a result of climate change.

Soil moisture deficit is generally expected to increase by up to 20 mm in central, northeastern, and southwestern China in response to changes in soil water-holding capacities associated with soil degradation (Figure 10c). However, moisture deficits in southeastern and northwestern China are not expected to change under the soil degradation scenario.

In the scenario with combined impacts of climate change and soil degradation on soil moisture deficits, climate change would dominate the overall pattern of and trends in moisture deficit change. However, the impacts of soil degradation would also be significant in locations such as central and southwestern China (Figure 10d).

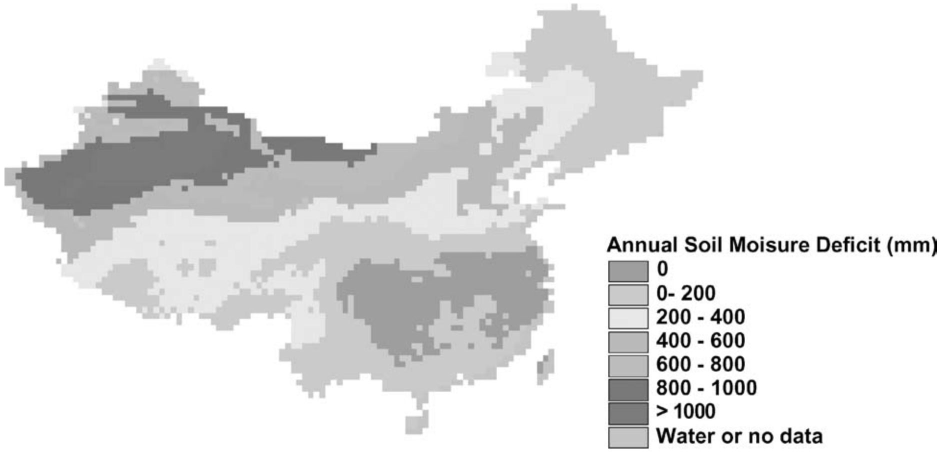
3.6. SURFACE RUNOFF

Surface runoff mainly occurs in southern and central China (Figure 11a). The highest values are found along the southeastern coast, where precipitation is high and soil water-holding capacity is relatively low.

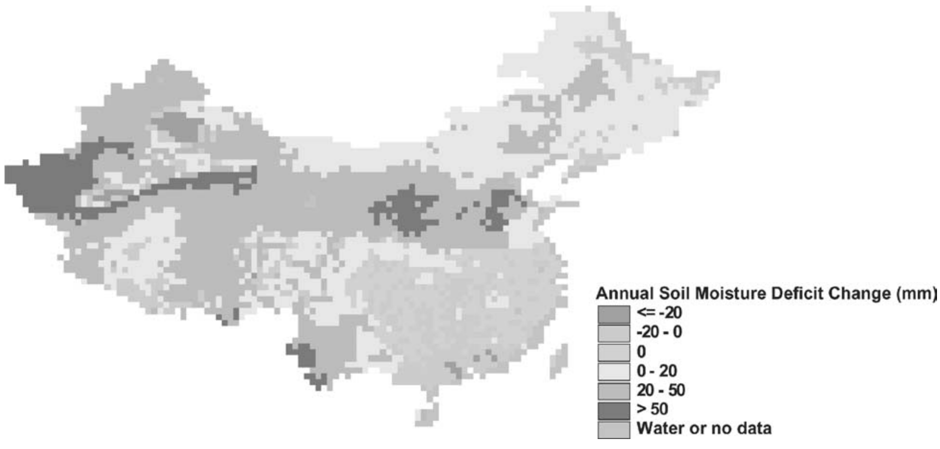
Under the climate change scenario, surface runoff would increase in southern China, mainly due to the expected change in precipitation, but would decrease along the eastern coast (Figure 11b). In northwestern China, surface runoff would remain at or near 0 mm because the expected increase in precipitation is not enough to offset the soil moisture deficit.

Under the soil degradation scenario, surface runoff would increase to nearly 30 mm in central, southwestern, and northeastern China (Figure 11c). However, surface runoff in southeastern and northwestern China would remain unchanged under this scenario.

Under the scenario that combines the impacts of climate change and soil degradation, climate change would dominate the general pattern of change in surface runoff. However, at some locations where soil degradation is serious, the impacts



(a)



(b)

Figure 10. Mean annual soil-moisture deficit in China for the 1961–1990 period (a) and changes in this parameter between the 2021–2030 and 1961–1990 periods under three scenarios: climate change (b), soil degradation (c), and climate change combined with soil degradation (d).

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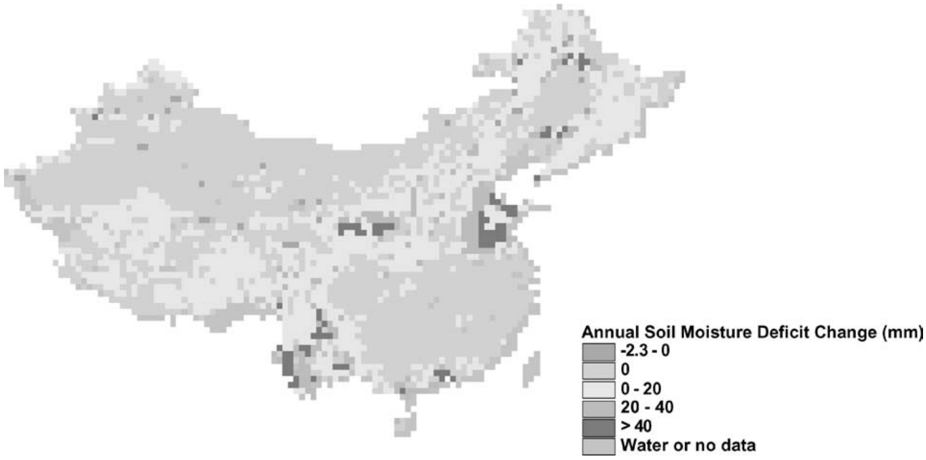
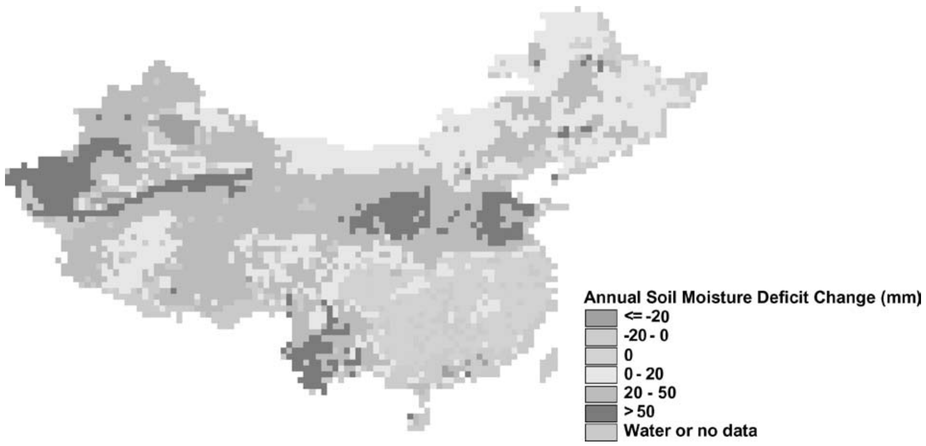


(c)



(d)

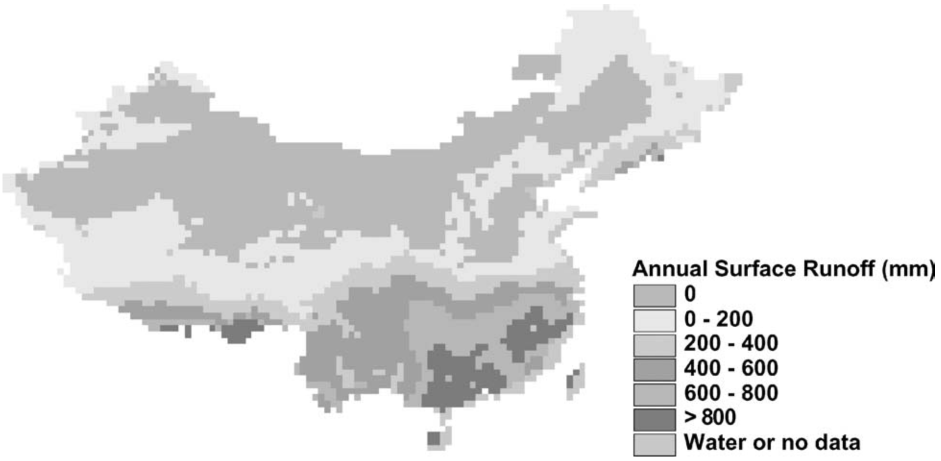
Figure 10. (*Continued*)

of soil degradation would be large enough to modify the impact of climate change. For example, in central and southwestern China and along the eastern coast, surface runoff is expected to decrease as a result of climate change alone; however, it is expected to increase under the combined impacts of climate change and soil degradation (Figure 11d).

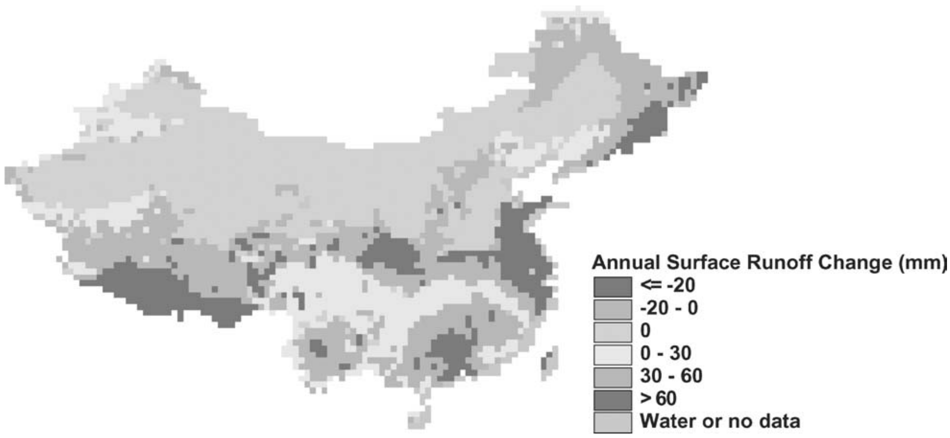
4. Discussion

4.1. CLIMATE CHANGE, SOIL DEGRADATION, AND WATER RESOURCES

Climate change, soil degradation, and their effects on water resources are closely related global environmental challenges. Climate change could have major impacts, including disastrous drought and floods, and may eventually increase the potential soil and ecological degradation in some regions. Soil degradation, in turn, would decrease soil water-holding capacity and increase the emission of greenhouse gases (Feng et al., 2001). Soil water-holding capacity, which integrates both soil quantity (depth) and soil quality (a set of physiochemical properties), is closely related to the soil's clay, silt, and organic matter contents as well as to total porosity. These properties determine not only the soil's suitability for plant growth but also its buffering capacity against climatic extremes. Decreases in soil water-holding



(a)



(b)

Figure 11. Mean annual surface runoff in China for the 1961–1990 period (a) and changes in this parameter between the 2021–2030 and 1961–1990 periods under three scenarios: climate change (b), soil degradation (c), and climate change combined with soil degradation (d).

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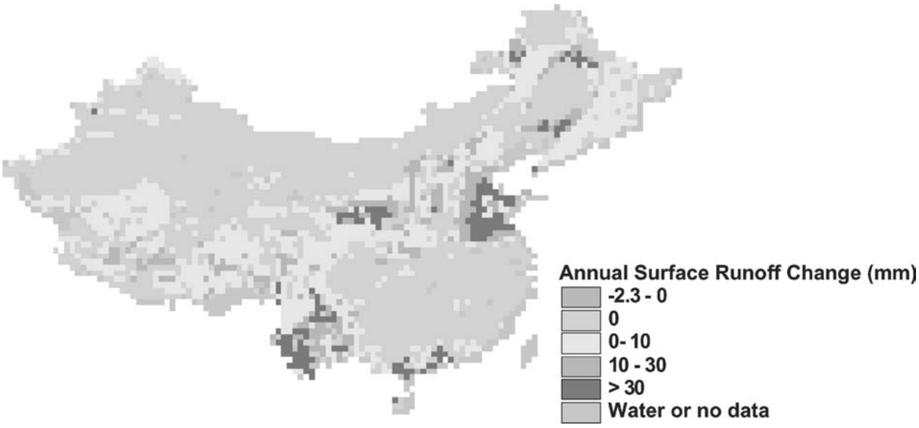
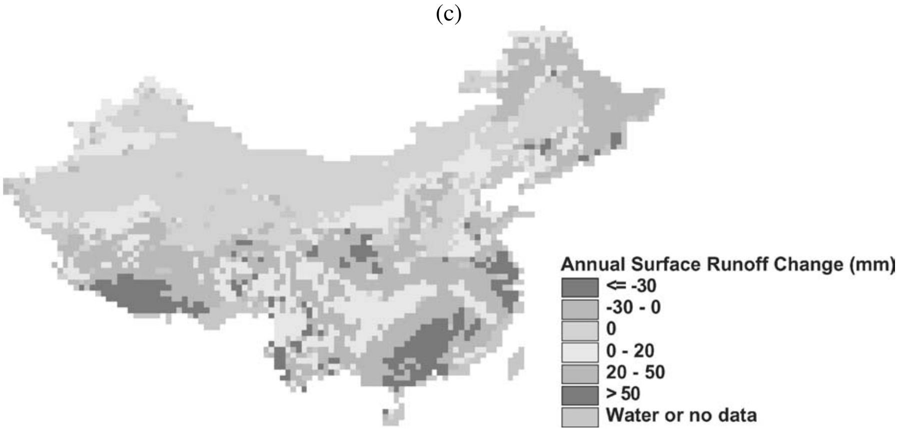


(c)



(d)

Figure 11. Continued

capacity will increase the potential for disastrous drought and floods. Our research results indicate that climate change and soil degradation will play important roles in regional problems with water resources.

4.2. IMPLICATIONS OF THE STUDY

The CRU climatologies have strict criteria for whether a station will be included and assume that time consistency is more critical than spatial sampling intensity. Thus, these climatologies have a poor distribution of spatial data in some more remote locations. For example, in regions near the Himalayas, where both precipitation and temperature are highly variable, small differences in location affect climate much more dramatically than do temporal changes in climate; thus, the assumption of the greater importance of temporal factors in such areas appears invalid. As a result, CRU climatologies differ greatly from the L&W climatologies (which have increased sampling intensity) in such areas (see also Legates, 1995). The Penman-Monteith method, as applied in the approaches to modeling global water balance, uses a standard log profile to extrapolate energy and humidity gradients, and relies on wind data that are more susceptible to variations in microclimate and to extrapolation or interpolation errors resulting from poor data sampling. There is an argument that poorly sampled data could devalue a improved model in estimation of PET and lead to large errors in water balance outputs (see also Legates and Mather, 1992). Therefore, considerable caution should be taken in selecting datasets for use in modeling and in predicting results for remote or developing regions for which data is sparse.

In the climate change scenario, there is considerable variation among the estimates provided by various GCMs for the future direction, magnitude, and timing of changes in precipitation (IPCC, 1996). Moving from the large scale of GCMs to finer resolutions, the problem of "downscaling" introduces new uncertainties. Extreme variability in climate (which is not addressed in the present paper) is itself sufficiently important to induce disastrous drought and floods. The interdecadal variability in climatology and its implications for water resources during the 1961–1990 period are also not addressed here.

ASSOD considered only soil degradation resulting from human disturbance, and separated out erosion processes that occur naturally or that are induced by climate. It used the degree of degradation to represent the current, static situation (measured by decreased or increased productivity compared with values 10–15 years ago), and used the rate of degradation to represent the dynamic nature of soil degradation, namely the change in degree over time. In the present study, we used the degradation rate to develop a soil degradation scenario for each grid cell. Feddema (1999) assumed that the degree of degradation would increase by one category and that the extent would increase by two categories (both homogeneously) across the African continent by the 2010–2039 period based on the assumption that the local population would double (or triple in some locations). Both the studies failed to adequately account for the influences of local policy and feedback from climate change on soil degradation, as well as the physical processes involved in this change.

Compared with the research on Africa (Feddema, 1999), we used updated databases for soil degradation and climatologies and different methods in calculating PET and developing soil degradation scenarios. Nevertheless, both studies agree on some general results. For example, the impacts of climate change on water resources on a continental or national scale would be greater than those of soil degradation. However, at some locations where soil degradation is a serious problem, the two factors could be on the same order of magnitude.

5. Conclusion

Water is one of the most critical resources in China. However, water resources are among the most vulnerable to climate change and human activities. In our study, we used a water-balance model and recent revised datasets to assess the impacts of climatic change, human-induced soil degradation, and their interactions on China's future water resources.

On a national scale, climate change dominates the spatial pattern and the overall trend for changes in water resources. However, where soil degradation is a serious problem, the impacts of soil degradation could be significant. For example, some regions in central, southwestern, and northeastern China would become more vulnerable to disastrous drought and floods as a result of soil degradation.

The impacts of climate change can offset or add to those of soil degradation. Under the combined impacts of climate change and soil degradation, soil moisture deficits would increase most in central, western, and southwestern China. Surface runoff would increase most in southeastern China. In these vulnerable regions, more efficient plant-, soil-, and water-management practices should be adopted.

The interactions between climate change or variability and soil degradation, and their effects on water resources, are complex and important. More detailed process-based models are needed to capture the key feedback mechanisms more effectively.

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