Farmland management effects on the quality of surface soil during oasification in the southern rim of the Tarim Basin in Xinjiang, China

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ABSTRACT

Oasification and desertification are basic geographical processes in arid areas, and both change the soil properties and quality. Recently, oasification has been obvious in the southern rim of the Tarim Basin of Xinjiang, China, and agriculture is the main land-use type. There has been little research on oasification involving farmland of different management types in extremely arid regions. In 2004, four experimental fields were established in the Cele Oasis, representing four typical land-use types of local farmers' tillage practices during oasification. Three experimental fields were situated in the desert-oasis ecotone: newly cultivated land (NEF), a field with normal manure input (NMF), and a field with high manure input (HMF); there was also another field in the oasis interior (OIF), to allow analysis of the management effects on soil properties and soil quality of farmlands. Additionally, the soil from an uncultivated control plot was analyzed for comparison. Both a Soil Quality Index based on soil properties and a Sustainable Yield Index based on yearly yield were used to assess the soil quality of the different farmlands. There were significant differences in seven soil indicators, including soil particle size distribution and soil organic matter, between the four locations. NEF had the lowest and OIF the highest values in all assessments among the five experiment plots. Fertilization of NMF and HMF had positive effects on soil properties and soil quality; however, the sustainable productivity of these farmlands was low. The results should be beneficial for refining agricultural management practices and improving sustainable land use in the oasification process.

Keywords: oasification; soil properties; soil quality; farmland; management; Cele

Oasification and desertification are basic geographical processes in arid areas (Wang 2009). Compared with the concept of desertification, which is generally understood to refer to land degradation in arid, semi-arid and dry semi-humid climatic zones (INCD 1994), oasification is still not a uniform concept and is often regarded as the process that converts desert to oases in arid zones (Su et al. 2007, Wang 2009). Both desertification and oasification have important effects on soil quality, which is defined as 'the capacity of a soil to function' (Karlen et al. 1997). Therefore, it is important to analyze soil quality and the direction of its change with time (Doran 2002), and to use these as primary indicators of sustainable land use and management (Doran 2002, Gong et al. 2006). Moreover, an analysis of changes in soil properties and soil quality due to human effects can support decision- and policy-making processes at regional and national levels.

The majority of analyses of soil properties (or soil quality) were conducted on soil of different land-use types with regard to desertification in arid, semi-arid or dry semi-humid climatic zones (Sharma et al. 2005, Gui et al. 2009a). Soil quality research in extremely arid regions (like the

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Xinjiang Uighur Autonomous Region of China), in regard to oasification and aimed at understanding the human effects on one land-use type, is much more limited. During the last 50 years, increasing population pressures have led to an indiscriminate exploitation of natural fragile lands for agriculture in northwestern China, particularly in the Xinjiang Uighur Autonomous Region. Many researchers have showed that oasis and desert areas are increasing simultaneously in Xinjiang, and the oasis-desert ecotone area is reducing gradually (Gui et al. 2009b), and thus the phenomenon of oasification has been clear in recent times. Oases located at the southern rim of the Tarim Basin, have encountered the same situation: the oasis-desert ecotone area is shrinking, and the oasis area is increasing. In the process of oases growth, farmland is increasing as the dominant land-use type. These changes have significant effects on soil properties; positive or negative, depending on the management intensities of the farmland by the local people. Since water is the main limiting factor in oases and for oasification, its combination with other limiting factors has a decisive influence on the management intensities of farmland in the process of oasis development (Gui et al. 2009a,b).

The Cele Oasis, located at southern rim of the Tarim Basin, has an extremely arid climate and was selected as a representative area with farmland under different management intensities. The objectives of this study were (1) to understand the effects of different farmland uses on soil properties, including soil particle size distribution (PSD) and soil organic matter (SOM); and (2) to evaluate the soil quality of different farmland uses from the overall soil quality index (SQI) based on principle component analysis (PCA) of measured soil nutrients, and the sustainable yield index (SYI) from a sustainable productivity perspective. Concluding suggestions are given for sustainable farmland use in the oases development of the southern rim of the Tarim Basin.

MATERIALS AND METHODS

Study area. This study was carried out in the Cele Oasis (35°17'–39°30'N, 80°03'–82°10'E), located in the middle part of the southern rim of the Tarim Basin and at the northern piedmont of the Kunlun Mountains. The research sites were limited to an elevation of 1340–1380 m (36°55'–37°10'N, 80°42'–82°55'E). The region has a typical arid continental climate with an average annual temperature of 11.9°C. Average annual precipitation and evaporation are 34 and 2595 mm, respectively. Wind is common year-round, with prevailing northwesterly winds. The soil is classified mainly as aeolian sandy soil. The Cele River, rising from the Kunlun Mountains, is the most important river and is closely linked with the development of the Cele Oasis. Its annual runoff is 1.27×10^8 m^3.

Like other oases, the Cele Oasis is mainly distributed on an alluvial plain, and has simple topography. Topographic and climatic factors determine the land-use types of the oasis to a lesser extent than in temperate, tropical or semi-arid regions. Farmland is the main land-use type, with cotton, maize and wheat being the main crops. In the desert-oasis ecotone, the vegetation is dominated by *Alhagi sparsifolia* Shap., with a coverage of about 38.9%.

Experiment layout and treatments. Farmland management intensities vary depending on many factors, such as position, years of utilization, the source of irrigation water, irrigation amount and the input of materials and management practices (Gui et al. 2009b). The experiments were initiated in 2004. Two fields, which had been cultivated for 15 years by the Cele National Station of Observation and Research for Desert-Grassland Ecosystem of the Chinese Academy of Science, were selected as experimental plots. One was named high manure farmland (HMF) and the other normal farmland (NMF), because the former had higher manure input than the latter in long-term management practice. In spring of 2004, a new field (NEF) was reclaimed near the two existing fields. These three fields are all situated in the desert-oasis ecotone. In addition, another field situated in the interior of the oasis (OIF) was selected, which had been cultivated for > 100 years by local farmers. Its fertilization rate was not significantly different from NMF. During the experiment, the fertilization rate of HMF, NMF and OIF was kept at the current levels, and the NEF did not receive any fertilizer (Table 1). Cotton was the main crop in all experimental fields. Annual yields from each field were recorded, from harvesting a plot of 1 ha every year.

Thus, four experimental plots were studied, which represented four typical farmland management intensities in the process of oasis development: (i) the OIF represented conventional management intensity, the irrigation water mainly coming from the Cele River; the HMF, NMF and NEF represented management intensities in the

Table 1. Characterization of the experimental plots

Experimental plot (0.15 ha)	Annual fertilizer amount (kg/h/m^2)			Utilization years (2009)	Position	Main source of irrigation water	Level
	farmyard manure	inorganic fertilizer TN	inorganic fertilizer TP				
CTP	–	–	–	–	ecotone	–	natural background
NEF	–	–	–	5	ecotone	ground water	oasis growth
NMF	21500	208	57	15	ecotone	ground water	oasis growth
HMF	30000	362	126	15	ecotone	ground water	oasis growth
OIF	12776	171	120	over 100	oasis interior	Cele river	relatively stable

CTP – control plot; NEF – new farmland; NMF – normal manure addition farmland; HMF – high manure addition farmland; OIF – oasis interior farmland

process of oasis growth due to economic and population pressures, the irrigation water mainly coming from groundwater. Among HMF, NMF and NEF; (ii) HMF represented a farmland use with high input of materials and energy, typical for people under good economic conditions; (iii) NMF represented farmland use with usual or less input of materials and energy, typical for people under general or poor economic conditions; and (iv) NEF represented a short-term use mode at water limited sites, and these may be abandoned at any time when sufficient irrigation water cannot be provided.

To better understand the difference in soil nutrient contents between the experimental fields, an uncultivated area near NEF was included as control plot (CTP). Soil samples from CTP served as a control and were used to compare to experimental plots to determine whether or not tillage practices were causing soil deterioration. The CTP represents the original natural land use in the desert-oasis ecotone. Detailed information about the experimental plots is presented in Table 1.

Soil sampling and measurements. Surface soil samples (0–20-cm deep) were collected from experimental plots after the harvest of cotton in October 2009. At least six samples were taken randomly from each plot. The soil samples were air-dried and afterwards sieved before determination of the following soil properties. Soil PSD was determined by laser diffraction analysis: the soil samples were pretreated with H_2O_2 (30%, w/w) at 72°C to destroy the organic matter, and the aggregates were then dispersed by adding sodium hexametaphosphate and sonicating the samples for 30 s, after which they were analyzed by a laser diffraction technique using a Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England) (Wang et al. 2008). SOM was determined by the Walkley-Black method (Nelson and Sommers 1982), total nitrogen (TN) was determined by the semi-micro Kjeldahl method, and total phosphorus (TP) was determined colorimetrically after the wet digestion with $H_2SO_4 + HClO_4$. Total potassium (TK) was determined by the flame photometer; available nitrogen (AN) by a microdiffusion technique after alkaline hydrolysis; and available K (AK) and available phosphorus (AP) were measured colorimetrically after extraction with 3% ammonium carbonate. In addition, extracts from saturated pastes of the samples tested were analyzed for electrical conductivity (EC), pH, sodium (Na^+) by emission spectrometry, calcium (Ca^{2+}) and magnesium (Mg^{2+}) by titration, and chloride (Cl^-) using a chloridometer.

To better characterize the soil PSD, fractal theory was used, i.e. the fractal dimension (*D*) was calculated according to PSD data; the higher the *D*-value, the better the PSD (Su et al. 2004, Wang et al. 2008, Gui et al. 2009a). Tyler and Wheatcraft's method (Tyler and Wheatcraft 1992) was used for the *D*-value calculation, using the equation:

$$\frac{V(r < R_i)}{V_T} = \left(\frac{R_i}{R_{\max}}\right)^{3-D} \quad (1)$$

Where: r is the particle size; R_i is the particle size of grade i in the particle size grading; $V(r < R_i)$ is the volume of soil particles with a diameter less than R_i; V_T is the volume of all of the soil particles, and R_{max} is the maximum diameter of the soil particles. Logarithms were taken for both sides of Eq. (1), and the *D*-values of all soil samples derived from the slopes of the logarithmic curves fitted to the data.

Soil quality index (SQI). To determine the SQI based on soil properties, three steps were followed: first, a minimum data set (MDS) of indicators that best represented soil function was selected; second, the MDS indicators were scored; and last, the indicator scores were integrated into a comparative index of soil quality. Only those soil properties that showed significant treatment differences were selected for the MDS. Significant variables were chosen for the next step in MDS formation through PCA (Andrews et al. 2002, Mandal et al. 2008). Principal components (PC) for a data set are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of the closest fit to n observations in a p-dimensional space, subject to being orthogonal to one another. The PCs with high eigenvalues and variables with high factor-loading were assumed to be variables that best represented system attributes. Therefore, only the PCs with eigenvalues ≥ 1 (Brejda et al. 2000) and those that explained at least 5% of the variation in the data (Sharma et al. 2005, Mandal et al. 2008) were first selected. Within each PC, only highly weighted factors were retained. Highly weighted factor-loadings were defined as having absolute values within 10% of the highest factor loading.

To reduce redundancy among the highly weighted variables within a particular PCA, Pearson's correlation coefficients were used to determine the strength of the relationships among variables (Andrews et al. 2002). The final variables were selected from each PC: (a) the variable with the highest factor loading as the most important contributor to the PC; (b) the variable with the highest correlation sum was considered to best represent the group since it is generally related to the other variables; and (c) the variable with the lowest correlation sums due to their implied relative independence from the group (Mandal et al. 2008). Well-correlated variables which met all the requirements above were considered redundant and only one with a high factor loading was considered (Sharma et al. 2005, Mandal et al. 2008).

After determining the indicators, every observation of each indicator was transformed using a linear scoring method (Andrews et al. 2002, Mandal et al. 2008). Indicators were arranged in order depending on whether a higher value was considered 'good' or 'bad' in terms of soil function. For 'more is better' indicators, each observation was divided by the highest observed value such that the highest observed value received a score of 1 while all others received a score of < 1. For 'less is better' indicators, the lowest observed value was divided by each observation; thus the lowest observed value received a score of 1 while all others received a score of < 1. For many indicators, such as pH, observations were scored as 'more is better' up to a threshold value and were then scored as 'less is better' above that threshold (Liebig et al. 2001). Once transformed, the indicators for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigenvectors > 1, provided the weighted factor (W) for variables chosen under a given PC. We then summed up the weighted variables' scores for each observation using the following equation:

$$SQI = \sum_{i-1}^{n} W_{\mathrm{i}} S_{\mathrm{i}} \qquad (2)$$

Where: S_i is the score for variable i and W_i is the weighting factor derived from the PCA. Higher index scores are assumed to mean better soil quality or superior performance of soil functions.

Sustainable yield index (SYI). In addition to soil quality from an environmental protection perspective, productivity is another important soil function. In our study, the SYI (Singh et al. 1990) was calculated (based on cotton yield) to evaluate the ability of soil to maintain sustainable productivity according to:

$$SYI = (\bar{Y} - \mathrm{s})/Y_{\mathrm{max}} \qquad (3)$$

Where: $\bar{Y}$ is the average yield of an experimental field; σ is the yield standard deviation and Y_{max} is the maximum yield in the field over years.

Statistical analysis. One-way analysis of variance (ANOVA) procedures were performed to assess the effects of different farmland use intensities on SOM and soil nutrients. If the main effects were significant at $P < 0.05$, a post-hoc separation of means was done by univariate LSD (least significant difference) test. ANOVA, LSD, PCA and Pearson's correlation analysis were conducted using the SPSS software (version 13.0).

RESULTS

Effects of different farmland management on soil properties. The laser particle analyzer can measure PSD values within a range of 0–2000 µm, and gives a continuous volume percentage of parti-

Table 2. Contents of soil properties of the different experimental plots

	CTP	NEF	NMF	HMF	OIF	F
D	2.10 ± 0.02^{c}	2.13 ± 0.03^{d}	2.14 ± 0.04^{c}	2.18 ± 0.02^{b}	2.22 ± 0.03^{a}	13**
SOM	2.20 ± 0.24^{b}	2.20 ± 0.31^{b}	4.15 ± 1.72^{a}	5.70 ± 0.80^{a}	5.69 ± 0.56^{a}	11.29**
TN	0.10 ± 0.01^{c}	0.11 ± 0.02^{c}	0.23 ± 0.09^{b}	0.30 ± 0.09^{ab}	0.37 ± 0.06^{a}	10.11**
TP	0.57 ± 0.01^{c}	0.58 ± 0.06^{c}	0.61 ± 0.02^{bc}	0.71 ± 0.22^{a}	0.73 ± 0.05^{a}	12.45**
TK	23.60 ± 0.03	23.35 ± 0.21	23.87 ± 0.32	23.70 ± 0.60	23.00 ± 0.61	1.974^{ns}
AN	1.67 ± 1.13	3.55 ± 0.62	10.60 ± 8.17	7.50 ± 2.42	11.23 ± 6.58	2.276^{ns}
AP	2.32 ± 0.96^{c}	1.14 ± 0.14^{c}	15.61 ± 5.02^{bc}	28.20 ± 3.30^{ab}	34.64 ± 22.22^{a}	6.38**
AK	154.67 ± 25.72^{a}	94.00 ± 11.36^{c}	118.33 ± 13.58^{bc}	128.33 ± 18.14^{ab}	120.66 ± 9.29^{bc}	5.12*
pH	8.90 ± 0.08^{a}	8.74 ± 0.11^{a}	8.74 ± 0.08^{a}	8.52 ± 0.20^{b}	8.45 ± 0.07^{b}	7.18**
EC	0.08 ± 0.02	0.08 ± 0.03	0.07 ± 0.01	0.08 ± 0.01	0.08 ± 0.02	0.16^{ns}
TC	0.62 ± 0.10	0.55 ± 0.06	0.61 ± 0.07	0.60 ± 0.06	056 ± 0.10	0.46^{ns}
HCO_3^-	0.14 ± 0.01	0.16 ± 0.03	0.15 ± 0.01	0.16 ± 0.02	0.15 ± 0.02	0.57^{ns}
Cl^-	0.04 ± 0.01	0.03 ± 0.02	0.04 ± 0.02	0.03 ± 0.01	0.04 ± 0.02	0.11^{ns}
Ca^{2+}	0.05 ± 0.01	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.01	0.06 ± 0.01	1.38^{ns}
Mg^{2+}	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.01	0.02 ± 0.00	0.02 ± 0.01	2.16^{ns}
Na^+	0.08 ± 0.02	0.07 ± 0.01	0.08 ± 0.02	0.07 ± 0.01	0.04 ± 0.02	3.46^{ns}

Values in each row with the same letter are not significantly (LSD) different between farmlands; $^{*}P < 0.05$; $^{**}P < 0.01$; ^{ns}not significant at $P < 0.05$

cle size in the soil PSD analysis. However, the PSD values in the present study were all in the range 0.35–1000 μm; therefore, the soil particle sizes in this range were graded into 64 fractions using the software provided with the laser particle analyzer to calculate *D* (Montero 2005, Wang et al. 2008, Gui et al. 2009a). According to Eq. (1), the *D*-values of sample plots changed in the range 2.01–2.24. The determination coefficients (R^2) of the linear regressions from Eq. (1) were high, with the range 0.86–0.95, indicating that the fractal model of the accumulative volume-size distribution was appropriate. Moreover, correlation analysis of the *D*-values and the volume contents of clay, silt and sand revealed significant positive correlations between the *D*-value and the contents of clay and silt ($r = 0.85$ and 0.81, respectively), and a significant negative correlation with sand content ($r = -0.79$). All correlation analyses passed a two-tailed test ($P < 0.01$), indicating that the *D*-value was a parameter that effectively reflected soil texture.

The *D*-values and other soil properties determined in this study of farmlands with differing management are presented in Table 2. There were significant differences between soils in *D*, SOM, TN, TP, AP and pH ($P < 0.01$), and in AK ($P < 0.05$). However, there were no significant differences in other properties between the four farmlands.

The *D*-values in soils from different experimental plots decreased in the following order: OIF > HMF > NMF > CTP > NEF. Multiple comparisons revealed that differences were significant between the four farmlands, but not significant between NMF and CTP (Table 2). The order of other soil properties that were significantly different between sample plots was broadly similar to that of *D*. Multiple comparisons revealed that OIF ≈ HMF > NMF > NEF ≈ CTP where the inequalities only indicate significant differences (Table 2).

The TK and AN did not show marked differences between the different plots; however, OIF and HMF tended to have high, and NEF low values. The CTP soil showed higher contents of TK and AN than the NEF soil. The EC, TC, Ca^{2+}, Mg^{2+}, Na^+, Cl^- and HCO_3^- also did not show marked differences between sample plots, and its values were similar, too (Table 2).

SQI. To select representatives from indicators that showed significant differences between the sample plots, for SQI calculation, we initially needed to reduce the redundancy indicators using PCA.

Table 3. Results of the principal component analysis of the statistically significant soil quality indicators

PCs	PC1	PC2
Eigen value	5.198	1.248
% of variance	74.252	17.830
Cumulative %	74.252	92.082
D	0.951	0.247
SOM	0.977	0.025
TN	0.990	–0.019
TP	0.989	–0.003
AP	0.997	0.049
AK	±0.031	0.998
pH	–0.950	0.269

PC – principal component. Underlined factor loadings are considered highly weighted when within 10 % of variation of the absolute values of the highest factor loading in each PC

In the PCA of seven variables, two PCs had an eigenvalue > 1 and explained 97% of the variance (Table 3). AP was the greatest contributor to PC1, given by the factor loading, so it was selected first. Except for AK, all other variables had highly weighted factor loadings, i.e. those with absolute values within 10% of the AP factor loading: *D*, SOM, TN, TP and pH, meaning that a further analysis was needed.

Pearson's correlation coefficients and correlation sums were derived for each of the highly weighted variables from PC1 individually (Table 4). The *D* had the highest correlation sum and was therefore selected as the indicator. The SOM, TN and TP were dropped because they were highly correlated with *D* ($r = 0.90$, 0.94 and 0.94, respectively). Although pH had the lowest correlation sum, it was dropped because it was also highly correlated with *D* ($r = 0.94$). Under PC2, only AK had a high factor loading, and so it was selected. Hence, AP, *D* and AK were the final indicators selected to calculate SQI. From the PCA, *W* was determined, Eq. (2), by dividing the percentage of variation in the data set explained by each PC that contributed to the indicated variable(s) by the total percentage of variation explained by all PCs with eigenvalues > 1 (Table 3). For AP, *D* and AK the *W* was 0.37, 0.36 and 0.14, respectively.

Finally, calculated SQIs were in the order OIF (0.84) > HMF (0.77) > NMF (0.62) > CTP (0.52) > NEF (0.45). The relative contribution of each indicator to the SQI is shown in Figure 1.

SYI. The SYI gives an idea of the overall yield sustainability, and was calculated on the basis of cotton yields of the different farmlands over five years. High SYI indicates better production stability. The SYI of OIF was the highest (0.78), and that of NEF the lowest (0.03). However, the SYI of HMF (0.28) was not higher but even lower than that of NMF (0.45) (Figure 2).

DISCUSSION

Farmland management effects on soil properties. In our five-year experiment, the *D* of soil PSD was significantly different between the four farmlands; the other six indicators (e.g. SOM) also had significant differences, and the order of the six soil properties was generally similar to that of *D*. This can be explained by the fact that the finer soil particles assisted binding of SOM and nutrients (Zalibekov 2002), and soil PSD plays a significant role in regulating soil nutrients (Basic et al. 2004, Su et al. 2004, Gui et al. 2009a). The

Table 4. Pearson's correlation coefficient and correlation sums for highly weighted variables with high factor loading under PC1

PC1 variables	D	SOM	TN	TP	AP	AK	pH
D	1.000	0.900*	0.939*	0.937*	0.956*	0.210	–0.921*
SOM	0.900*	1.000	0.977**	0.956*	0.985**	–0.003	–0.904*
TN	0.939*	0.977**	1.000	0.959*	0.994**	–0.057	–0.925*
TP	0.937*	0.956*	0.959*	1.000	0.976**	–0.027	–0.963**
AP	0.956*	0.985**	0.994**	0.976**	1.000	0.016	–0.923*
AK	0.210	–0.003	–0.057	–0.027	0.016	1.000	0.291
pH	–0.921*	–0.904*	–0.925*	–0.963*	–0.923*	0.291	1.000
Correlation sum	4.022	3.910	3.888	3.838	4.004	1.431	–3.365

*$P < 0.05$; **$P < 0.01$

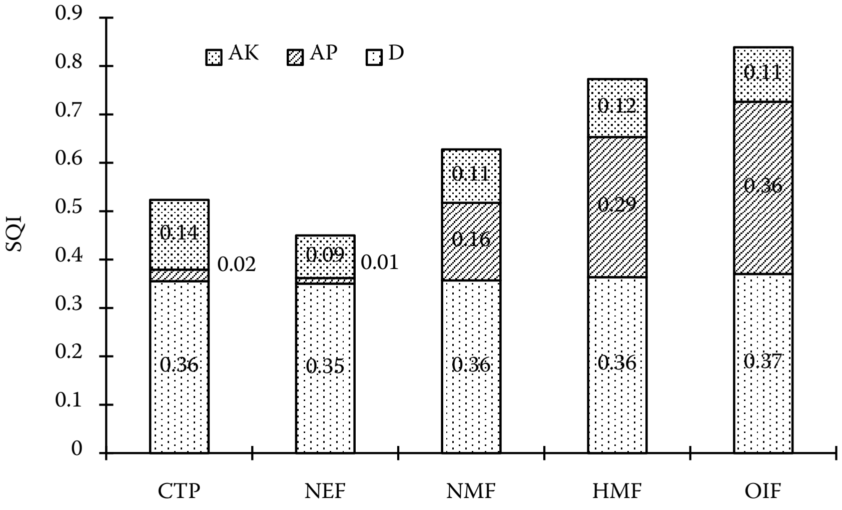

Figure 1. Soil quality indexes of the farmlands under different management and the individual contribution of each of the key indicators

correlation analysis between *D* and the other six indicators also indicated that the soil PSD had an important effect on soil nutrients (Table 3). There were no significant differences in the other eight indicators (e.g. TK). Whether differences were significant or not, all soil properties were at lower levels compared with other areas such as semi-arid zones. This may be due to the particular background of the soil and climatic conditions (Sharma et al. 2005, Gui et al. 2009b).

The management intensities of the farmlands in the desert-oasis ecotone significantly affected soil properties. The soil PSD and nutrients of HMF and NMF, which had high inputs of materials and energy, were at high levels, and clearly improved compared with CTP. This indicated that a positive management has positive effects on soil PSD and nutrients during the process of oasification. The soil properties of NEF, which had no input other than irrigation, had the lowest levels, and were not significantly different from CTP; additionally, many values of soil nutrients were even lower than in CTP (Table 2). This result indicates that the managing of NEF did not have positive effects on soil properties during the oasification process.

In comparison with the HMF and NMF soil in the desert-oasis ecotone, the soil PSD and nutrient of the OIF soil were higher, although the manure addition was lower than for HMF and was not different from that of NMF. This result indicates that there was no simple linear correlation between manure addition and soil properties. Thus, the effects of farmland management on soil nutrient contents were complex. Since the OIF was in the interior of oasis and had more years of utilization than HMF and NMF, it is assumed that the period of utilization and the spatial locations of farmlands were the primary reasons for the differences in PSD and other soil properties. The difference in the utilization time of farmland can result in different degrees of soil maturation (Wang and Zhao 2009, Gui et al. 2009b). Moreover, the farmlands in or near the oasis interior are mainly irrigated by the Cele River which comes from the Kunlun Mountains. This river carries large amounts of silt and nutrients which could have beneficial effects on soil. In addition, the vegetation coverage in the study area differed due to the different spatial locations of farmlands, and thus the response of farmlands to wind erosion also differed by being

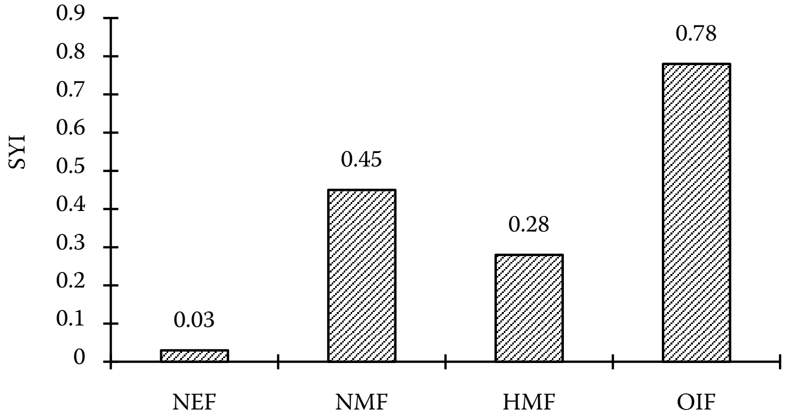

Figure 2. The sustainable yield indexes of different farmland uses

subject to different perennial prevailing winds (Su et al. 2004, Gui et al. 2009b).

OIF had higher soil nutrient contents than other experimental farmlands, however, the soil PSD and nutrient contents, especially the SOM content, were low compared to other areas of China. This may be attributed to a combination of serious soil erosion and lower carbon (C) inputs (Gui et al. 2009a,b). Our field investigation showed that crop residues such as cotton stalks are fed to animals or used as fuel for cooking. So, only low amounts of residues are returned to the cropland, resulting in low C inputs. Therefore, a higher C input such as manure addition and return of crop residues could be very useful to ameliorate the soil fertility.

Assessment of soil quality under different farmland managements. SQIs were calculated to evaluate the effects of different farmland management on soil properties from an environmental perspective. These indexes showed a similar order as did *D*-values: OIF > HMF > NMF > CTP > NEF.

Thus, the farmland management represented by NEF must be judged as harmful from an environmental point of view of oasification. Under the given climatic extremes poor agricultural management will significantly contribute to land degradation and deterioration of soil quality.

However, the NMF and HMF soils showed higher SQI compared to CTP. This result differs from results of other regions. Many investigations conducted in temperate and tropical regions or semi-arid areas indicated that soil quality decreases after land use shifts from original natural land use (forest, woodland or grassland) to cultivation (Lepsch et al. 1994, Wang et al. 2003). In these other regions, cropland had the lowest level of soil quality of all land uses. Thus, the comparably high background values of soil properties of the original natural systems in these regions decreased under cultivation. In contrast, very low natural resources are typical for many arid areas (Sharma et al. 2005). The soils are often coarse-textured; inherently low in fertility, organic matter and water holding capacity; and susceptible to wind and water erosion (Su et al. 2004, Sharma et al. 2005, Gui et al. 2009b).The fragile natural resources in arid areas result in low background values of soil properties, and thus the input of materials and energy from outside increases the contents of soil nutrients or other properties. The SQI of NMF and HMF all showed a higher level than the CTP which represents the original natural system.

A soil considered to be of high quality for one function may not be good for other functions (Nortcliff 2002). Although the HMF had positive effects on soil nutrients, its SYI of 0.28 was much lower than SYI = 0.78 of OIF. This is due to the fact that its yearly yield changed greatly and was not stable compared to that of OIF. The SYI = 0.45 of NMF was higher than that of the HMF, but NMF had lower yields than OIF. NEF not only had large changes in yearly yield but also had the lowest yields in every year, and so had the lowest SYI of 0.03. These results indicated that the farmland management represented by HMF, NMF and NEF was not optimal from a sustainable productivity perspective.

Implications for sustainable farmland use during oasification. It has been highlighted that climatic extremes, fragile natural resources and poverty are the main factors threatening soil quality and productivity, and consequently sustainable farmland use in the oases of the southern rim of the Tarim Basin. There are several options to mitigate the land degradation induced by farmland use.

Firstly, the farmland should be reclaimed prudentially in the desert-oasis ecotone, and particularly the short-term use (NEF) should be reduced or eliminated, since this mode leads to soil deterioration and also results in low productivity. When farmland is reclaimed, the water resource state must be considered and guaranteed to sustain tillage. The addition of manure and other materials (such as crop residues) to the farmland must also be guaranteed; this can improve soil qualities as well as increase crop yields. Further increasing the vegetation cover around farmlands is needed to reduce wind erosion.

The second option is that the advanced irrigation techniques should be used to save river water and groundwater. In many oases, and especially the Cele Oasis, flood irrigation is still the only irrigation mode. Ineffective use of water resources is the main problem in the oasis and the oasification process (Wang 2009). Using advanced irrigation techniques can enhance the efficiency of water use and effectively protect groundwater. The water table is at a depth of about 15 m in the desert-oasis ecotone; however, in many areas it is as deep as 30 m. Since the rooting depth of *A. sparsifolia* is 12–30 m (Gui et al. 2009b) , a water table below 30 m could seriously affect their growth.

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