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Types and Mechanisms of Science-Driven Institutional Change: The case of desertification control in northern China

Lihua Yang* and Chen Li
School of Public Administration and Workshop for Environmental Governance and Sustainability Science, Beihang University, Beijing, China

ABSTRACT
Science plays an important role in institutional change, but the types and mechanisms of science-driven institutional change have received little attention in the mainstream discourse concerning institutions, institutional change and social governance. Comparing 25 cases using data from surveys, interviews, observations and a meta-analysis of archives regarding desertification control in northern China, this study found that, although science influenced the results of desertification control through influencing institutional change, its influence was also constrained by the types and working principles of science-driven institutional change. When analyzing the application of different methods of desertification control, the type of biological control that dominates the interaction (biological-control-dominant interaction) may be that of science-driven intuitional change variables with the highest desertification control performance, whereas for the participants in desertification control the type of high participation and multiple interactions may be the variable with the greatest influence. This study also proposes nine principles for effective science-driven institutional change that address collaborative, effective and sustainable applications and extensions of advanced scientific methods, effective collaboration among various social actors and organizations, and localized, collaborative and nested laws, regulations and rules regarding desertification control. Stronger rules result in more effective science-driven institutional changes. These findings provide an outline for reforming the models of science-driven institutional change and implementing future science and technology policies for desertification control and other types of ecological and environmental governance. This study also provides a theoretical and empirical foundation for further research concerning science-driven institutional change. Copyright © 2015 John Wiley & Sons, Ltd and ERP Environment

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Keywords: institution; collaboration; collaborative governance; combating desertification; science and technology

*Correspondence to: Lihua Yang, School of Public Administration and Workshop for Environmental Governance and Sustainability Science, Beihang University, Beijing, China. E-mail: journeyylh@163.com

Introduction

Numerous studies have emphasized the role of science in desertification control (Bauer and Stringer, 2009; Reynolds *et al.*, 2007; Thomas, 1997; Winslow *et al.*, 2011; Yang, 2009, 2010a; Yang *et al.*, 2010; Yang and Wu, 2009, 2010) and the influence of institutional arrangements on the adoption and implementation of scientific measures in ecological and environmental governance (Akhtar-Schuster *et al.*, 2011; Garcia and Charles, 2008; Lidskog and Sundqvist, 2002; McNie, 2007; Yang and Wu, 2010). Yang *et al.* (2013) also showed that science influences the institutional changes in desertification control, as many studies of the role of technology in institutional change in other fields had already found (Anderson and Hill, 1975; Binswanger and Ruttan, 1978; Day, 1967; Marx and Engels, 1968; Lin, 1989). However, little is known about the types and mechanisms of institutional change driven by the adoption and implementation of scientific measures (or scientific applications).

Studying the types and mechanisms of science-driven institutional change is important for further understanding the role of science in institutional change and the relationship between science and institutional change. In contrast to regression, which only studies the relationship between two variables (e.g. science and institutional change), taxonomy can help explore the inner structure of science-driven institutional change; concepts such as 'sometimes-true-theories' (Coleman, 1964, p. 516) focus on 'how' (Davis and Marquis, 2005) through describing 'a set of interacting parts—an assembly of elements producing an effect not inherent in any one of them' (Hernes, 1998, p. 74). Furthermore, studying the types and mechanisms of science-driven institutional change can provide concrete guidance for policy makers and practitioners to make more scientific decisions and implement these decisions more effectively. Thus, the research questions of the present study are as follows. (1) What is the relationship between science-driven institutional change and the results of desertification control? (2) What are the primary types of successful science-driven institutional change? (3) What are the primary mechanisms of successful science-driven institutional change?

Theoretical Framework, Methods and Data

Conceptual Background and Theoretical Framework

Although there is ambiguous, inconsistent and overlapping use of terminology regarding institutions in the literature, institutions are often defined as sets of formal or informal behavioral rules (Lin, 1989; North, 1981, 1990, 1994a, 1994b; Ostrom, 1990, 2005; Ruttan, 1978; Schultz, 1968; Yang and Wu, 2012). Institutional change is the process of the production, development, replacement, transformation and transaction of institutions through which one or one set of institutions become another institution or set of institutions (Yang, 2010a; Yang and Wu, 2012). Because no institutions are in absolute equilibrium or completely stable, institutional change is the most common state in which institutions exist (Yang, 2009). In desertification control, the simple criterion for evaluating the success of institutional change is whether desertification control results improve after the institutional change.

Previous studies found that, in addition to biophysical conditions such as longitude, latitude and annual average evaporation (Gobin *et al.*, 2000; Miller *et al.*, 2010; Stringer *et al.*, 2009; Wang *et al.*, 2010; Yang, 2009; Yang *et al.*, 2013; Yang and Wu, 2012), the role of science in desertification control could be influenced by (1) the types of scientific method of desertification control and their relationships and accompanying extension services (Watson *et al.*, 2008; Yang, 2009; Yang *et al.*, 2013), (2) the types of social participant and their interactions in desertification control programs (Beunen and Opdam, 2011; Chittenden, 2011; Nelson *et al.*, 2008; Pellant *et al.*, 2004; Reynolds *et al.*, 2007; Seely, 1998; Seely and Moser, 2004; Thomas and Twyman, 2004; van Rooyen, 1998; Wang *et al.*, 2010; Watson *et al.*, 2008; Yang, 2009, 2012; Yang *et al.*, 2010, 2013) and (3) the types of law, regulation and rule of desertification control and their relationships (Akhtar-Schuster *et al.*, 2011; Barrera-Bassols *et al.*, 2006; Garcia and Charles, 2008; Lidskog and Sundqvist, 2002; Thomas, 1997; Yang, 2009; Yang *et al.*, 2010, 2013; Yang and Wu, 2010, 2012). In particular, the application of different methods of desertification control and the participants in desertification control strongly influenced the types of institutional change in desertification control, while all

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three aforementioned aspects affected the mechanisms of institutional change (Yang, 2009; Yang *et al.*, 2013; Yang and Wu, 2010, 2012). Thus, we primarily studied the types and mechanisms of science-driven institutional change influencing the results of desertification control in terms of the three aforementioned aspects, which proposed a theoretical framework for understanding the primary types and mechanisms of science-driven institutional change, the relationship between science-driven institutional change and the results of desertification control, and the interactions among multiple types and levels of institutional arrangements in the mechanisms of institutional change (Figure 1).

Research Design and Sites

This study is based on a case study of 12 field sites and a meta-analysis of 13 other studies of regions in Inner Mongolia, Ningxia, Gansu, Heilongjiang, Xinjiang and Qinghai in northern China that have suffered desertification problems for thousands of years (see Figure 2). The field study was conducted in 12 counties that span three

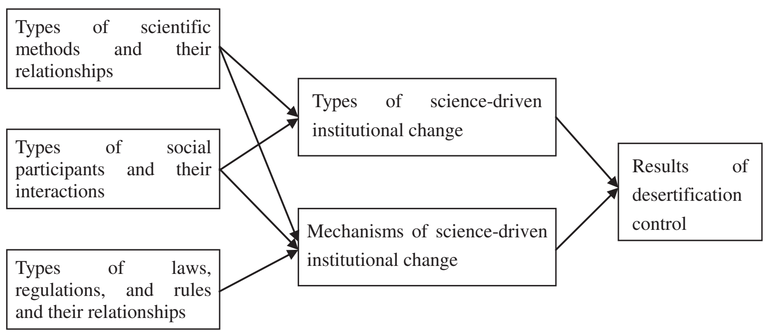

Figure 1. Theoretical framework

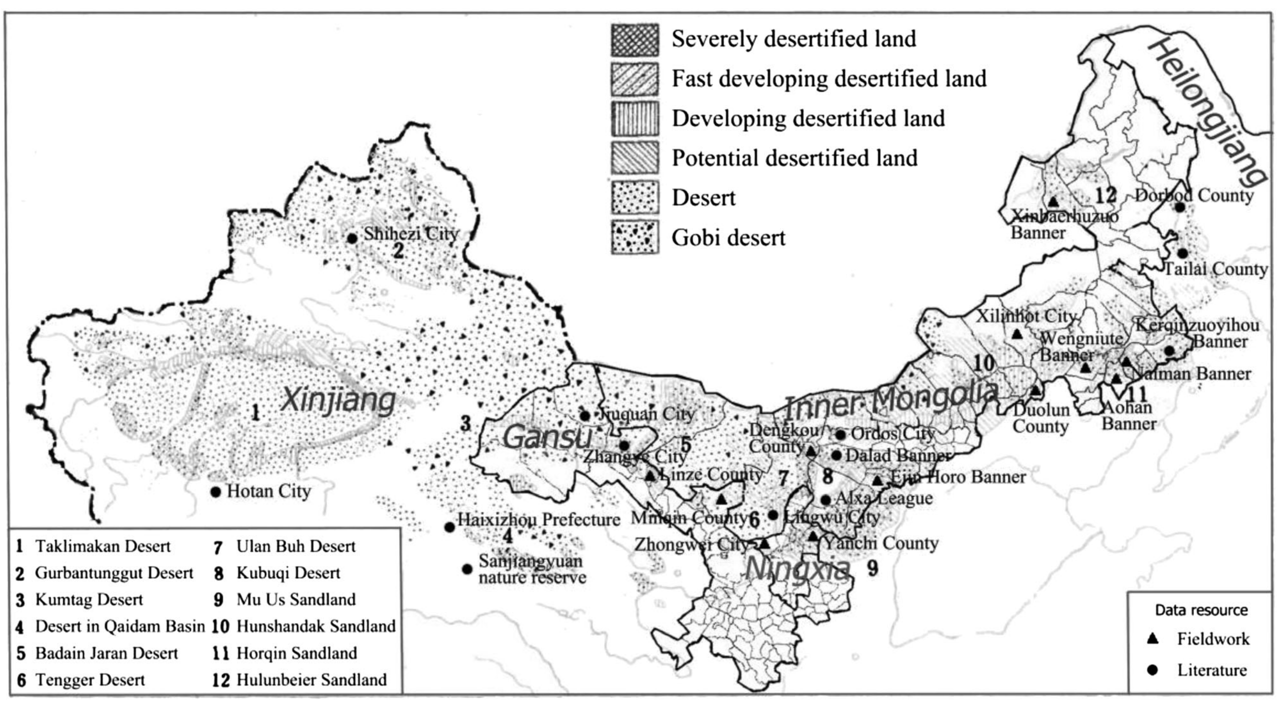

Figure 2. The 25 research sites and their jurisdictions (base map source: Shi and Chang, 2003)

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adjacent providences (Inner Mongolia, Ningxia and Gansu). To test causal generalization by changing coverage and to consider spatial-scale effects (Gibson *et al.*, 2000; Wu, 2007), a meta-analysis was conducted for four counties, eight prefectures and one nature reserve (covering 14 counties in four prefectures and one township in another prefecture). Eight of the sites were located in arid zones, six were located in transitional zones between arid and semi-arid regions, two were located in semi-arid zones and nine were located in transitional zones between semi-arid and semi-humid regions (Yang *et al.*, 2013) (Table 1).

Data Acquisition

The data used in the study were a combination of four types of datum, i.e. interviews, surveys, observations and archives (Singleton and Straits, 2005). A four-year field study was conducted from June 2006 to December 2011 in 12 counties. We first performed interviews of 118 interviewees in Minqin, Linze and Zhongwei from June 2006 to February 2008 and in the other counties from July to August 2011; the random-sampling surveys were from March to December 2011. We received 4406 valid responses, which correspond to a valid rate among received copies of >93% (Table 2). The interviewees included people recommended by various related organizations (such as desert control stations and governmental bureaus) and volunteers from the county seats and rural villages. Because many village farmers cannot read Chinese and high school students often come from all areas of the county, meaning that a random sample of students can be used to represent the entire population, we distributed the survey questionnaires to high school students and trained them to help family members, relatives and neighbors answer the questions. This method has been used in multiple studies and has been proven to be a valid and efficient method for collecting data in rural China (Yang, 2011, 2012; Yang *et al.*, 2013). To complement the data from the interviews and surveys, participatory and non-participatory observations were conducted during the same period as the interviews at 52 sites, such as desert control stations, the Bureau of Forestry, typical areas of desertification control and famous natural reserves. Archival materials, such as government gazettes, county annals, government documents, research reports, historical memoirs, official web materials and published and non-published literature from 1949 to 2011, were extensively collected to complement the data from the field study. These materials were also used for a comparative analysis and synthesis of the 13 non-field-study cases, which were selected based on recommendations of experts in the field, their representativeness of desertification control and the potential of obtaining research data. Thus, in addition to the scientific research design, the diverse types of respondent and the large sample size ($N=4406$), which could guarantee high consistency between respondents' perception and actual situations of desertification control (Yang, 2009, 2012; Yang *et al.*, 2010, 2013; Yang and Wu, 2010), the supplemental data based on interviews, observations, archives and literature for the 12 field study cases and the 13 non-field-study cases also reduced the deviations between respondents' perception and actual situations of desertification control.

Variables and Measurements

According to the aforementioned theoretical framework, the primary research variables of the study were (1) the impact of science on institutional change regarding desertification control, (2) the types of scientific method of desertification control and their extension, (3) the types of social participant and their interactions in desertification control, (4) the laws, regulations and rules regarding desertification control and (5) the results of desertification control. Furthermore, based on many years of experience in China, the methods of desertification control in the study were grouped into four types: (1) mechanical controls (such as high sand dike stabilization using a mechanical sand fence and straw checkerboard dune stabilization); (2) chemical controls (such as chemical dune stabilization); (3) biological controls (such as biological dune stabilization methods); (4) agricultural controls (such as deep plowing, improved slowing techniques, strip intercropping, retaining crop residues and other methods used in agricultural production to prevent desertification) (Yang *et al.*, 2013). The types of primary social actor studied included (1) farmers and herders, (2) households and communities, (3) the general public, (4) businesses, (5) governments, (6) scholars (including scientists, experts and technicians), (7) research institutes (including desertification control stations, universities and colleges), (8) the media, (9) religious groups, (10) non-governmental organizations and (11) international organizations (Yang, 2009, 2012; Yang *et al.*, 2013). The laws, regulations and rules of desertification control studied could be divided into three types or layers (Kiser and Ostrom, 2000; North, 1990; Yang, 2009): (1)

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Counties	Provinces	Longitude	Latitude	Climate division	Total area (km^2)	Population (ten thousand)	Annual average temperature (°C)	Annual average precipitation (mm)	Annual average evaporation (mm)
The 12 field study sites									
Linze County	Gansu	99°51′E–100°30′E	38°57′N–39°42′N	arid	3 148	15	7.7	115	2212
Minqin County	Gansu	101°49′E–104°12′E	38°03′N–39°27′N	arid	16 016	27.4	7.8	115	2644
Zhongwei City	Ningxia	104°17′E–105°37′E	36°59′N–37°42′N	arid	5 780	109.29	9.5	188	1914
Yanchi County	Ningxia	106°30′E–107°47′E	37°04′N–38°10′N	arid	8 661	15.7	7.7	<300	>2000
Dengkou County	IM[a]	106°09′E–107°10′E	40°09′N–40°57′N	arid	3 554	9.6	7.6	145	2398
Ejin Horo Banner	IM	108°58′E–110°25′E	38°56′N–39°49′N	arid–semi-arid	5 600	15.5	6.7	348	2563
Xinbaerhuzuo Banner	IM	117°33′E–120°12′E	46°10′N–49°47′N	arid–semi-arid	22 000	4.2	−0.3	268	1650
Xilinhot City	IM	115°13′E–117°06′E	43°02′N–44°52′N	semi-arid	15 179	25.2	1.6	250–350	1746
Naiman Banner	IM	120°19′E–121°35′E	42°14′N–43°32′N	semi-arid	8 159	41.9	6 to −6.5[c]	366	1973–2082
Duolun Banner	IM	115°51′E–116°54′E	41°46′N–42°36′N	semi-arid–semi-humid	3 773	10.3	1.9	389	1714
Wengniute Banner	IM	117°49′E–120°43′E	42°26′N–43°25′N	semi-arid–semi-humid	11 882	41.6	4.5	370	2106
Aohan Banner	IM	119°30′E–120°53′E	41°42′N–43°02′N	semi-arid–semi-humid	8 294	51.3	5–7	310–460	2161.7
The 13 meta-analysis cases									
Hotan (Hetian) City	Xinjiang	79°85′E–80°11′E	36°92′N–37°29′N	arid	24 780	195	6–8	35	2480
Shihezi City	Xinjiang	84°85′E–86°40′E	43°20′N–45°20′N	arid–semi-arid	45 684	64	6.5–7.2	125–208	1000–1500
Sanjiangyuan Nature Reserve	Qinghai	89°45′E–102°23′E	31°39′N–36°12′N	semi-arid–semi-humid	1396 890	55.6	1–5	240–600	730–1700
Haixizhou Prefecture	Qinghai	90°06′E–99°42′E	35°01′N–39°20′N	semi-arid–semi-humid	325 785	38	0.5–5.2	16.7–487.7	1354–3526
Jiuquan City	Gansu	92°09′E–100°20′E	37°58′N–42°48′N	arid	19 200	110	3.9–9.3	84	2141
Zhangjie City	Gansu	97°20′E–102°12′E	37°28′N–39°57′N	arid–semi-arid	40 874	127	6	198	1400–2700
Lingwu City	Ningxia	106°21′E–106°89′E	37°50′N–38°35′N	semi-arid–semi-humid	4 639	23.7	≥10	206.2–255.2	2200
Alxa (Alashan) League	IM	97°10′E–106°52′E	37°21′N–42°47′N	arid	270 000	18	6–8.5	40–200	2400–4200
Ordos City	IM	106°42′E–111°27′E	37°35′N–40°51′N	arid–semi-arid	8 700	159	6.2	200	2506
Dalad (Dalate) Banner	IM	109°10′E–110°45′E	40°00′N–40°30′N	arid–semi-arid	8 200	34	6.1–7.1	240–360	2160
Kerqinzuoyihou Banner	IM	121°30′E–123°42′E	42°40′N–43°42′N	semi-arid–semi-humid	11 570	40.6	5.3–5.9	358–483	1900
Tailai County	Heilongjiang	123°11′E–123°33′E	46°23′N–47°12′N	semi-arid–semi-humid	3 996	32	4.9	392.6	1765
Dorbod (Duerbote) County	Heilongjiang	123°77′E–124°70′E	45°88′N–47°14′N	semi-arid–semi-humid	3 996	25.05	3.6	365–405	1774

Table 1. Characteristics of the 25 study sites
[a]The year the source was published.
[b]IM refers to Inner Mongolia.
[c]In some counties, because the data came from different sources, we only determined the annual average intervals rather than the annual average values for some factors.
Sources: Yang *et al.*, 2013; Wen, 2007.

	Linze	Minqin	Zhongwei	Yanchi	Dengkou	Ejin Horo	Xinbaerhuzuo	Xilinhot	Naiman	Duolun	Wengniute	Aohan	Total
a. Interview distribution													
Farmers or residents	4	6	5	1	1	2	2	1	1	1	1	1	26
Scholars, experts & technicians	3	11	4	4	2	3	0	4	5	0	2	4	42
Government officials	1	11	1	3	6	3	3	4	1	3	5	4	45
Businessmen	0	0	0	0	0	0	0	0	2	0	2	0	4
Religious groups or NGOs	0	1	0	0	0	0	0	0	0	0	0	0	1
Total	8	29	10	8	9	8	5	9	9	4	10	9	118
b. Survey distribution													
Number of copies sent	450	450	450	450	450	450	450	450	450	450	460	450	5410
Response rate (%)	75.78	100	80.00	99.56	72.00	38.89	86.00	93.56	96.00	100	100	100	86.82
Number of valid responses	328	418	345	439	304	150	387	342	424	449	458	362	4406
Valid rate among responses (%)	96.19	92.89	95.83	97.99	93.83	85.71	100	81.23	98.15	99.78	99.57	80.44	93.78
c. Types of survey respondent													
Farmers	97 (29.57)[b]	382 (91.39)	130 (37.68)	75 (17.08)	72 (23.68)	53 (35.33)	186 (48.06)	76 (22.22)	70 (16.51)	149 (33.18)	438 (95.63)	256 (70.72)	1984 (45.03)
Middle school teachers & students	91 (27.74)	8 (1.91)	58 (16.81)	166 (37.81)	99 (32.57)	38 (25.33)	45 (11.63)	99 (28.95)	134 (31.60)	135 (30.07)	11 (2.40)	21 (5.80)	905 (20.54)
General research institutes [a]	0 (0)	1 (0.24)	2 (0.58)	27 (6.15)	2 (0.66)	0 (0)	5 (1.29)	3 (0.88)	11 (2.60)	15 (3.34)	0 (0)	2 (0.55)	68 (1.54)
Desert control stations	0 (0)	0 (0)	0 (0)	2 (0.46)	2 (0.66)	0 (0)	1 (0.26)	0 (0)	2 (0.47)	8 (1.78)	0 (0)	0 (0)	15 (0.34)
Government	14 (4.27)	1 (0.24)	9 (2.61)	15 (3.42)	13 (4.28)	4 (2.67)	14 (3.62)	24 (7.02)	5 (1.18)	32 (7.13)	1 (0.22)	9 (2.49)	141 (3.20)
Businesses	55 (16.77)	8 (1.91)	48 (13.91)	55 (12.53)	53 (17.43)	10 (6.67)	18 (4.65)	63 (18.42)	14 (3.30)	34 (7.57)	4 (0.87)	28 (7.73)	390 (8.85)
Rural grassroots organizations	7 (2.13)	9 (2.15)	24 (6.96)	15 (3.42)	4 (1.31)	2 (1.33)	2 (0.52)	4 (1.17)	2 (0.47)	41 (9.13)	0 (0)	10 (2.76)	120 (2.72)
Organizations for technology development and promotion in rural areas	4 (1.22)	1 (0.24)	0 (0)	3 (0.68)	2 (0.66)	0 (0)	4 (1.03)	2 (0.58)	3 (0.71)	1 (0.22)	0 (0)	1 (0.28)	21 (0.48)
Universities	1 (0.31)	1 (0.24)	5 (1.45)	18 (4.10)	0 (0)	0 (0)	4 (1.03)	4 (1.17)	12 (2.83)	0 (0)	0 (0)	0 (0)	45 (1.02)
Religious groups	0 (0)	0 (0)	2 (0.58)	4 (0.91)	0 (0)	0 0	0 (0)	2 (0.58)	2 (0.47)	0 (0)	0 (0)	0 (0)	10 (0.23)
Other public institutions	25 (7.62)	1 (0.24)	25 (7.25)	10 (2.28)	20 (6.58)	16 (10.67)	10 (2.58)	40 (11.70)	3 (0.71)	13 (2.90)	3 (0.66)	26 (7.18)	192 (4.36)
Non-governmental organizations	5 (1.52)	0 (0)	5 (1.45)	4 (0.91)	3 (0.99)	6 (4)	1 (0.26)	3 (0.88)	2 (0.47)	1 (0.22)	0 (0)	2 (0.55)	32 (0.73)
News media	1 (0.31)	0 (0)	1 (0.29)	2 (0.46)	0 (0)	1 (0.67)	0 (0)	3 (0.88)	5 (1.18)	0 (0)	0 (0)	0 (0)	13 (0.30)
International organizations	0 (0)	0 (0)	4 (1.16)	2 (0.46)	0 (0)	0 (0)	1 (0.26)	0 (0)	15 (3.54)	0 (0)	0 (0)	1 (0.28)	23 (0.52)
Other	28 (8.54)	6 (1.44)	32 (9.27)	41 (9.33)	34 (11.18)	20 (13.33)	96 (24.81)	19 (5.56)	144 (33.96)	20 (4.46)	1 (0.22)	6 (1.66)	447 (10.15)
d. Observation distribution													
Numbers	4	11	7	2	9	2	2	2	5	3	2	3	52

Table 2. Survey and interview distribution in the 12 counties in northern China (2006–2011)

[a]'Types of organization' refers to the people in these organizations.

[b]Numbers in brackets are the percentages of the valid responses.

Sources: Yang *et al.*, 2013; Wen, 2007.

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laws and regulations regarding desertification control; (2) the operative mechanisms of laws and regulations; (3) concrete rules regarding desertification control.

For the variables that measured the primary desertification control methods and the participation of multiple organizations, we asked the respondents about the primary control method using a single-choice question and about the participation of organizations using a multiple-choice question for the 1950s, 1960s, 1970s, 1980s, 1990s and 2000s and then calculated their average responses. We used a six-point scale ('very large, large, medium, moderately small, very small, and unknown' and 'strongly agree, agree, neutral, moderately disagree, strongly disagree, and unknown') in the surveys to evaluate the impact of science on institutional changes in desertification control, the types of law, regulation and rule regarding desertification control, the results of desertification control and other related variables. However, for the variables in the 13 meta-analysis cases, we coded the above variables twice using three levels (i.e. high, middle and low) based on archive data. The values were first coded by one author and then independently verified by another author. If the results of the cases were different, coders met to agree on a value. To compare the cases in both the field studies and meta-analysis, we also translated the results of the field study cases to three levels when necessary (by dividing the distance from the maximum to the minimum by three). However, because the survey results did not provide enough information to make coding decisions on the working principles of science-driven institutional change in the 12 field study cases, archives, interviews and observational data were also used following the same method as in the 13 meta-analysis cases as a complement when necessary.

Results

Relationship Between Science-Driven Institutional Change and the Results of Desertification

Although the evaluations by the survey respondents from different counties were quite different, more than 30% of respondents indicated that the average impact of science on institutional change was 'very large' or 'large', and when 'medium' was included the percentage increased to 62.3% (Figure 3(a)). Furthermore, the factors impacting changes of laws, regulations and rules, from greatest to least, were laws and regulations, concrete rules, and operative mechanisms of laws and regulations (Figure 3(b)–(d)).

The average impact of science on institutional change was highly correlated with the results of desertification control efforts (Cohen *et al.*, 2002). Furthermore, the order of the coefficients for the impacts of the three types of institutional change on desertification control results, from the greatest to least, was operative mechanisms of laws and regulations, laws and regulations, and concrete rules (Figure 3(e) and Table 3).

Types of Science-Driven Institutional Change and their Performance

Types I–IV: Based on the Application of Different Desertification-Control Methods

The results indicated that, based on the application of the different methods of desertification control during approximately the last 60 years, science-driven institutional changes can be classified into four types. (1) Type I: biological controls become dominant over agricultural controls. This type was represented by four counties, Aohan, Xilinhot, Duolun and Wengniute. The primary feature of this type was that the primary sand control methods have been dominated by biological and agricultural strategies. However, although the use of biological controls has rapidly increased in recent decades, and became the main desertification control method circa 2000, agricultural controls played a role in the earlier decades. Mechanical and chemical controls were relatively uncommon. (2) Type II: biological-control-dominant interaction. This type was represented by three counties: Yanchi, Ejin Horo and Xinbaerhuzuo. Similar to Type I, the most important feature of this type is that biological controls have exhibited a rapid upward trend over the past 60 years, and became the leading desertification control circa 2000. However, in contrast with Type I, although biological controls were the primary method of desertification control in these regions, other controls could also be the most important method during different periods, such as agricultural controls in Yanchi in the 1980s and chemical controls in Ejin Horo in the 1980s. (3) Type III: agricultural-control-dominant interaction. This type was represented by the two counties of Dengkou and Naiman. The primary feature

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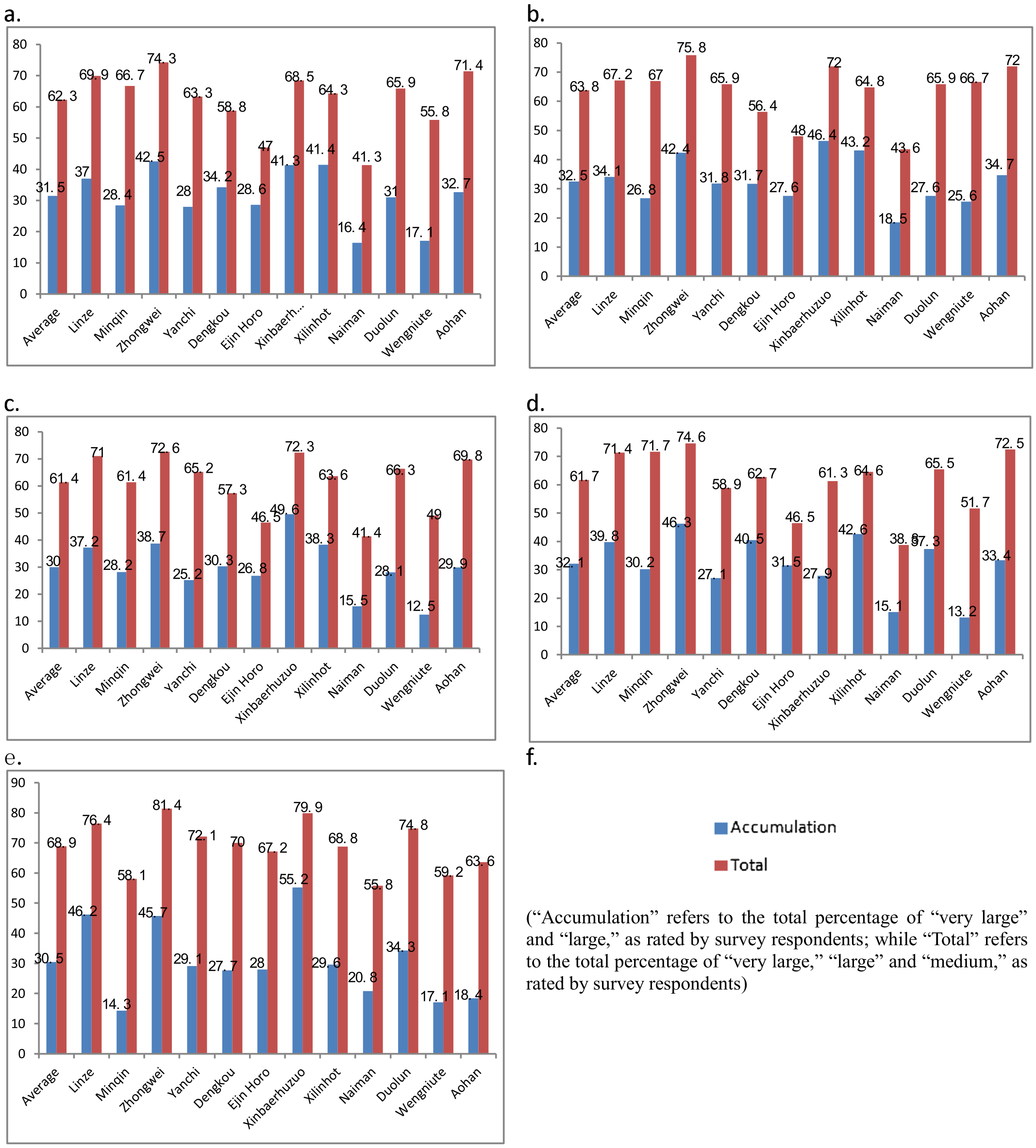

Figure 3. (a) Average evaluation of the three types of institutional change. (b) Concerning changes in laws and regulations regarding desertification control. (c) Concerning changes in the operative mechanisms of laws and regulations. (d) Concerning changes in concrete rules regarding desertification control. (e) Result of desertification control. (f) Legends

of this type was that agricultural controls had been the primary desertification control method during the past 60 years. The proportion of desertification control methods that were agricultural increased steadily and reached its highest value after 2000. Furthermore, biological controls had also played an important role in the past 60 years and became the second most used method after 2000; their role was much higher than for mechanical or chemical controls. (4) Type IV: interactions among the different methods of desertification control. This type was represented by the three counties of Minqin, Zhongwei and Linze. The most obvious feature of this type was that after 2000 two or three types of desertification control technology were used in combination, and the interaction among a variety of desertification control technologies, such as mechanical, biological and agricultural controls in Minqin and mechanical and biological controls in Zhongwei, was the primary driving force to promote desertification control in these areas (Figure 4). The interview data also supported the above classification. For example, an expert in Wengniute

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Variables	Results of desertification control			
	Accumulation[a]		Total[b]	
	Coefficients	Significance	Coefficients	Significance
Average impact on the three types of institutional change	0.711***	0.009	0.607**	0.036
Impact on changes in laws and regulations	0.694**	0.012	0.511*	0.090
Impact on changes in the operative mechanisms of laws and regulations	0.792***	0.002	0.737***	0.006
Impact on changes in concrete rules	0.457	0.135	0.482	0.112

Table 3. Pearson's correlation coefficients for the impact of science on institutional change with the results of desertification control, as rated by the survey respondents in the 12 counties (2011)
[a]Sum of the percentages of 'very large' and 'large,' as rated by survey respondents.
[b]Total of the percentages of 'very large', 'large' and 'medium,' as rated by survey respondents.
[c] ***$P < 0.01$, **$P < 0.05$, *$P < 0.10$ (two tailed).

strengthened the importance of the method of biological strategies, and interviewees in Naiman highlighted the method of agricultural controls.

Types A–D: Based on the Participants in Desertification Control

Based on the participants in desertification control, science-driven institutional changes could also be divided into four types. (1) Type A: government domination. This type was represented by the five counties of Linze, Zhongwei, Dengkou, Xilinhot and Duolun. The primary feature of this type was that government intervention exhibited a rapidly increasing trend and had obvious advantages compared with other participants in desertification control. Furthermore, in this type, the primary participants were the government and farmers, and the participation of other social actors was relatively low. The highest participation of farmers was in the 1950s and 1960s, and afterward their participation declined continuously. (2) Type B: interactions with the government's participation becoming dominant over farmers' participation. This type was represented by the four counties of Minqin, Naiman, Wengniute and Aohan. Similar to Type A, the primary feature of this type was that the government was the dominant social actor in desertification control and farmers were the second most important actors, although the role of farmers declined with time. However, in contrast with Type A, although government and farmers were the primary social actors in desertification control, other actors, such as families in Wengniute in the 1960s and 1970s and communities in Minqin in the 1970s, were also leading participants during a specific period. (3) Type C: low participation and multiple interactions. This type was represented by the two counties of Xilinhot and Yanchi. In this type, although the participation of all types of social actor was relatively low (most of the values were less than 25%) (Figure 5), many actors participated in desertification control and interactions among multiple actors became the primary driving force for desertification control. Furthermore, different actors were the leading participants in different periods. For example, the leading participants in Yanchi were families in the 1960s, communities in the 1970s and the public in the 1980s. (4) Type D: high participation and multiple interactions. This type was represented by the single county of Xinbaerhuzuo. Similar to Type C, the primary feature of this type was that various actors participated in desertification control, and collaboration among social actors was the primary force driving desertification control. Furthermore, the leading actor for each period was inconsistent. However, in contrast with Type C, the participation rates of actors were relatively high (many of them were greater than 25%) (Figure 5). Many interviewees had similar ideas. For example, interviewees in Dengkou emphasized the important roles of government, and interviewees in both Yanchi and Xilinhot emphasized the interactions among multiple social actors.

Performances of Types I–IV and A–D

By comparing the results of different counties with different types of science-driven institutional change (Table 4), this analysis suggests that the performance of Types I–IV was, from highest to lowest, Type II, Type IV, Type I and

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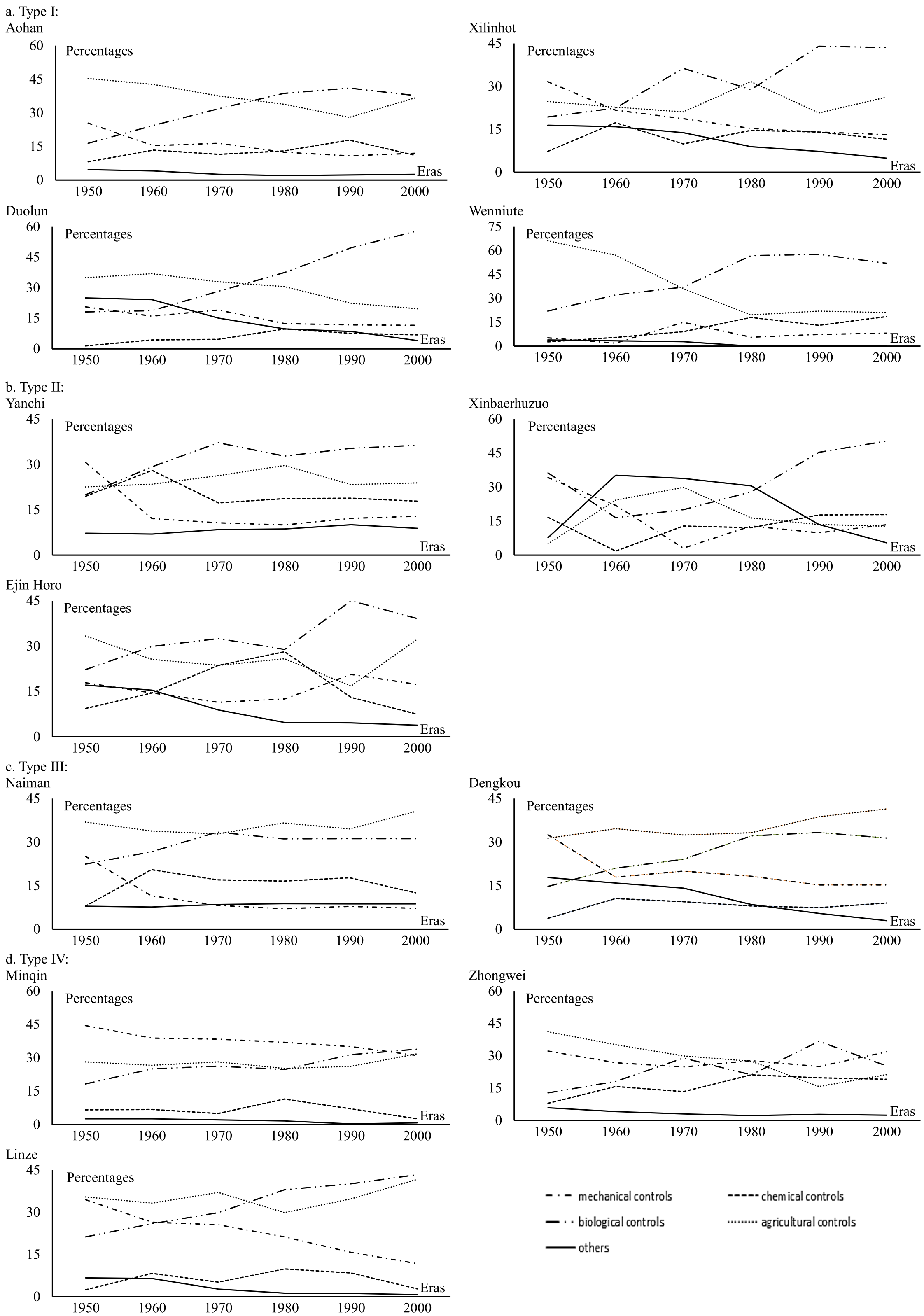

Figure 4. Types of science-driven institutional change based on the application of different types of desertification control

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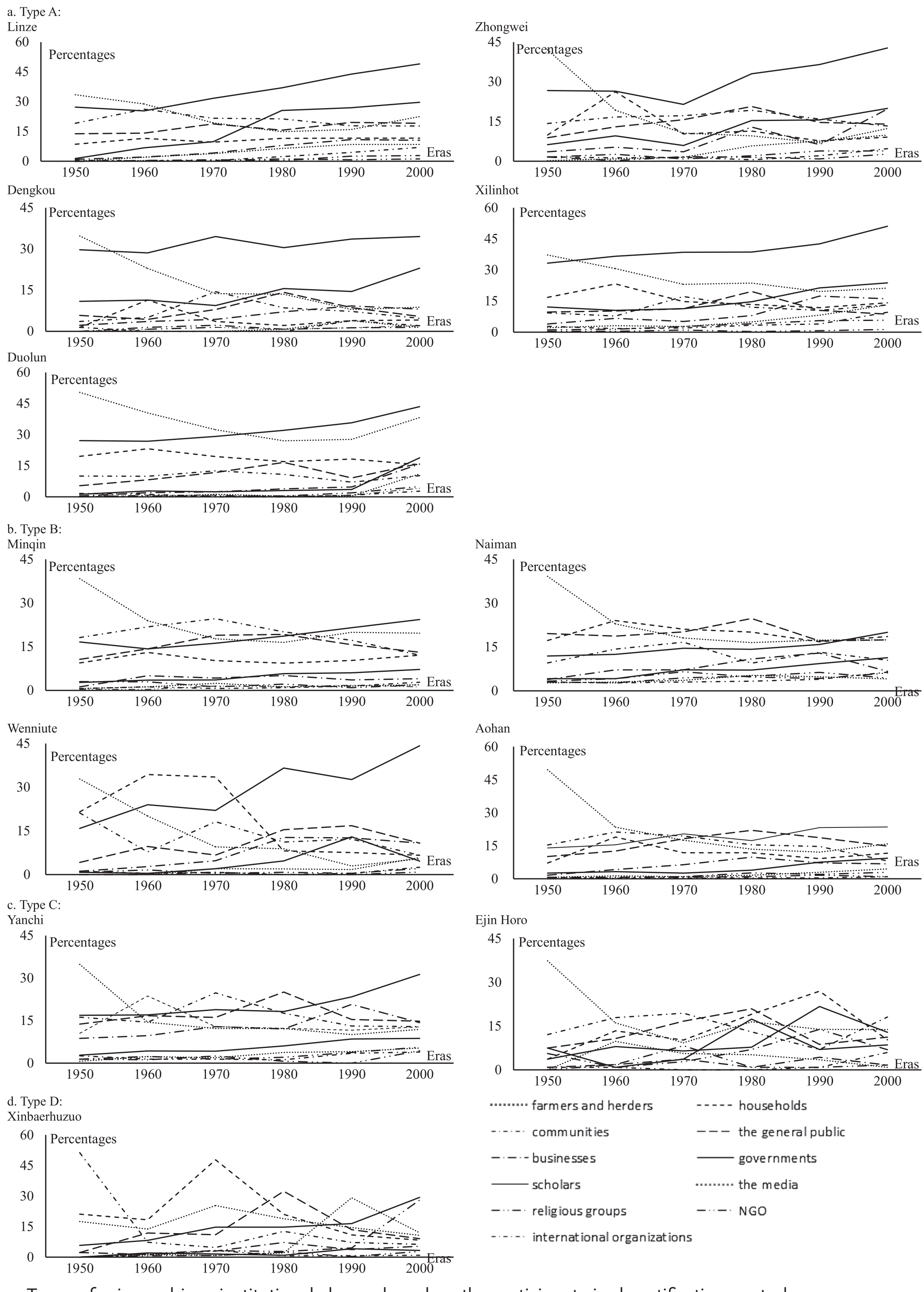

Figure 5. Types of science-driven institutional change based on the participants in desertification control

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Options	Linze (%)	Minqin (%)	Zhongwei (%)	Yanchi (%)	Dengkou (%)	Ejin Horo (%)	Xinbaerhuzuo (%)	Xilinhot (%)	Naiman (%)	Duolun (%)	Wengniute (%)	Aohan (%)
Results of DC [a]	46.2	14.3	45.7	29.2	27.7	28	55.2	29.6	20.8	34.3	17.1	18.4
Three levels of results	H	L	H	M	L	M	H	M	L	M	L	L
Types I–IV	IV	IV	IV	II	III	II	II	I	III	I	I	I
Average results [b]	35.4			37.5	24.3			24.9				
Types A–D	A	B	A	C	A	C	D	A	B	A	B	B
Average results [c]	36.8	17.7		28.6			55.2					

Table 4. The results of desertification control for the 12 counties and their types of science-driven institutional change
[a]Desertification control results as rated by the survey respondents who indicated that the results were 'very large' or 'large'.
[b]Average desertification control results for the counties of Types I–IV.
[c]Average desertification control results for the counties of Types A–D.

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Type III. Type II was the type of science-driven intuitional change with the highest desertification control performance, whereas Type III was the type with the lowest performance. Furthermore, the study indicated that the performance of Types A–D was, from highest to lowest, Type D, Type A, Type C and Type B. Type D was the type of science-driven institutional change with the highest desertification control performance, whereas Type B was the type with the lowest performance.

Modes 1–16, Defined by Combining Types I–IV and A–D, and their Performances

By combining Types I–IV and Types A–D, we divided science-driven institutional changes into 16 modes (Modes 1–16; see Figure 6). The abscissa lists Types I–IV in order of their performance, increasing successively from left to right. The ordinate list Types A–D in order of performance, increasing from bottom to top. Thus, we defined a matrix that classified science-driven institutional changes into 16 modes. In this matrix, Mode 13 (the combination of Type II and Type D), which had the highest governance performance according to the two dimensions (the abscissa and ordinate or the scientific methods and the evaluation of the participants), could be considered the ideal type of science-driven institutional change for desertification control, whereas Mode 4 (the combination of Type III and Type B), which had the lowest governance performance, could be considered the worst type; the other modes were between these two extremes (Modes 13 and 4).

Mechanisms of Successful Science-Driven Institutional Change

Through a combination of analysis of the types of science-driven institutional change and further studies regarding the factors that influence science-driven institutional change based on the aforementioned theoretical framework, we determined nine major working principles that influence the results of desertification control, which were combined into three more general principles (Table 5). Based on translating the results of the 12 field studies into three levels (i.e. high, middle and low) and the aforementioned qualitative coding procedure for the 13 meta-analysis cases, we used the nine working principles to code the 25 cases (Table 6). Furthermore, using the same coding procedures as stated above, we coded the influence of science on institutional change in desertification control and the desertification control project performance as high, middle or low.

We performed a chi-squared test (Greenwood and Nikulin, 1996) to evaluate whether these working principles resulted in differences in the desertification control performance. Analysis was performed using SPSS Statistics 17.0. The results indicated the chi-squared values were all high (from 11.577 to 52.769) and their asymptotic significances were all approximately zero (Table 7). Thus, we could conclude that these working principles influenced the performance of desertification control at the 0.05 significance level. The results also demonstrated that, except for

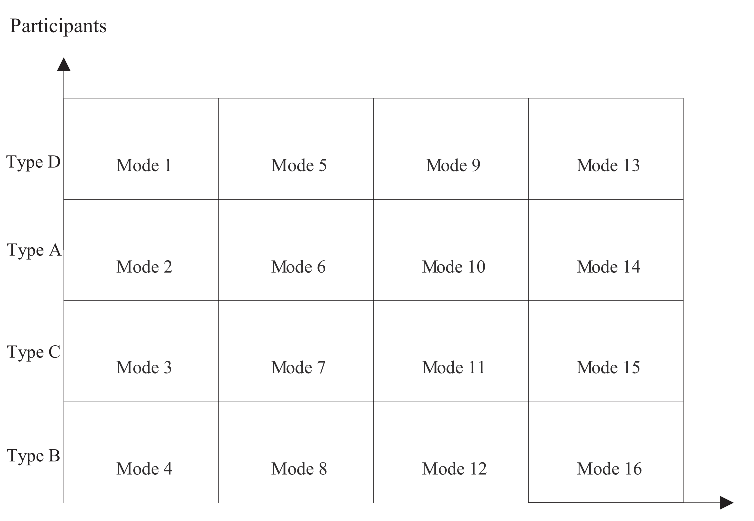

Figure 6. Matrix of the types of science-driven institutional change

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Major Principle I. There are collaborative, effective, and sustainable applications and extensions of advanced scientific methods for desertification control.
Working Principle 1. Biological controls provide major technical support for combating desertification.
Working Principle 2. Agricultural controls provide technical supplements to biological and other technologies.
Working Principle 3. There is effective synergy among different types of scientific methods for desertification control.
Major Principle II. There is effective collaboration among various social actors and organizations.
Working Principle 4. Government is a primary participant that guides programs for combating desertification but does not suppress the participation of other social actors and organizations.
Working Principle 5. Other social actors and organizations, such as farmers (or herders), families, communities and scholars, participate in desertification control and play an effective role.
Working Principle 6. There are coordination, communication and conflict-resolution mechanisms among the various social actors.
Major Principle III. There are localized, collaborative and nested laws, regulations and rules regarding desertification control.
Working Principle 7. There are localized, collaborative and nested laws and regulations regarding desertification control.
Working Principle 8. There are localized, collaborative and nested operation mechanisms for laws and regulations regarding desertification control.
Working Principle 9. There are localized, collaborative and nested rules and methods for desertification control.

Table 5. Nine working principles for successful science-driven institutional change in desertification control

Principles 2, 4, 5 and 6, the chi-squared values of the working principles weighted by the desertification control performance were higher than the chi-squared values of the principles weighted by the overall influence of science on institutional change. Furthermore, the asymptotic significances of the nine principles weighted by the performance of desertification control (which ranged from 0.000 to 0.003) were less than or equal to the significances weighted by the overall influence of science on institutional change (which ranged from 0.000 to 0.030). This result suggests that these principles may have more influence on the results of desertification control than on the overall influence of science-driven institutional change (Table 7).

We also performed a chi-squared test to evaluate whether these working principles resulted in differences in the types of science-driven institutional change. The results indicated that most of chi-squared values were high (from 5.429 to 55.964) and their asymptotic significances were all approximately zero (Table 7). Thus, we could conclude that these working principles influenced the types of science-driven institutional change at the 0.1 significance level. Furthermore, the results indicated that the chi-squared values of Types I–IV weighted by the influence of science on institutional change and the results of desertification control were not significant. This result suggested that differences in Types I–IV did not determine the levels of the influence of science on institutional change and the results of desertification or that their relationships were also influenced by other factors (such as the nine principles). However, the chi-squared values of Types A and B weighted by the influence of science on institutional change and the results of desertification control were both significant; this result suggested that the effects of Types A and B on the influence of science on institutional change and the results of desertification control were higher than the effects of Types I–IV. According to the chi-squared values, the overall influence of science on institutional change did not significantly influence the results of desertification control (this was different from the result shown in Table 3) and Types I–IV, whereas it influenced Types A and B at the 0.05 significance level. Moreover, Types A and B influenced Types I–IV, whereas Types I–IV had no significant influence on Types A and B. Thus, Types A and B could affect the results of desertification control, the overall influence of science on institutional change and Types I–IV, whereas Types I–IV affected none of them.

Discussion

Science Influences the Results of Desertification Control through Influencing Institutional Change, but the Influence is Constrained by the Types and Mechanisms of Science-Driven Institutional Change

The results of this study (Figure 3 and Table 3) indicate that science not only influences institutional change but also influences the results of desertification control through its influence on institutional change relevant to

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Cases	Influence of science on IC [a]	Types I–IV	Types A–D	Nine working principles									Project performance
				Principle 1	Principle 2	Principle 3	Principle 4	Principle 5	Principle 6	Principle 7	Principle 8	Principle 9	
The 12 field study cases													
Linze	H [b]	IV	A	M	H	H	H	H	M	M	M	H	H
Minqin	L	IV	B	L	M	H	M	M	M	L	M	M	L
Zhongwei	H	IV	A	L	M	H	H	M	M	H	H	H	H
Yanchi	L	II	C	M	M	M	M	M	M	M	M	M	M
Dengkou	M	III	A	L	H	M	H	L	M	M	M	H	L
Ejin Horo	M	II	C	M	M	H	L	M	H	M	M	M	M
Xinbaerhuzuo	M	II	D	M	L	H	L	M	H	H	H	M	H
Xilinhot	H	II	C	M	M	M	H	H	M	H	H	H	M
Naiman	L	III	B	L	H	L	L	H	H	L	L	L	L
Duolun	M	I	A	M	M	M	H	H	M	M	M	H	M
Wengniute	L	I	B	H	H	L	M	M	M	L	L	L	L
Aohan	L	I	B	M	H	L	H	M	H	M	M	M	L
The 13 meta-analysis cases													
Hotan (Hetian) City	M	I	B	H	H	M	H	M	M	L	M	H	L
Shihezi City	M	I	A	M	M	M	H	M	L	H	M	M	M
Sanjiangyuan Nature Reserve	H	I	C	H	H	M	H	H	H	M	H	H	M
Haixizhou Prefecture	M	III	A	M	M	M	H	L	L	M	M	M	H
Jiuquan City	M	III	C	M	M	M	H	H	ND	M	M	M	M
Zhangjie City	L	II	A	M	M	M	H	M	M	M	H	M	H
Lingwu City	M	IV	C	H	H	M	H	H	H	L	L	M	M
Alxa (Alashan) League	H	IV	C	H	H	H	H	H	M	L	M	H	L
Ordos City	H	IV	A	H	H	H	H	H	M	H	H	M	H
Dalad (Dalate) Banner	M	II	A	H	M	H	H	H	M	H	M	M	H
Kerqinzuoyihou Banner	M	IV	C	H	H	H	H	H	L	M	H	H	M
Tailai County	H	III	B	M	H	H	H	M	M	M	L	M	H
Dorbod (Duerbote) County	L	III	A	M	M	M	H	H	M	M	M	ND	H

Table 6. Comparison of the types of science-driven institutional change and satisfaction of the nine working principles

[a] IC, institutional change.

[b] H, high; M, middle; L, low; ND, no data.

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	The influence of science on IC [a]	Types I–IV	Types A–D	P1	P2	P3	P4	P5	P6	P7	P8	P9
The results of desertification control	3.500	1.846	22.923	18.500	19.192	17.808	52.769	15.846	21.640	14.115	11.577	24.041
(sig.)	0.174	0.605	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.001	0.003	0.000
The influence of science on IC	–	2.160	18.000	9.880	19.840	16.840	57.880	16.360	21.875	7.000	10.840	18.898
(sig.)	–	0.540	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.030	0.004	0.000
Types I-IV	2.667	–	18.841	14.952	21.810	18.667	41.143	25.810	29.548	5.429	16.381	26.742
(sig.)	0.264	–	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.066	0.000	0.000
Types A-D	7.429	1.286	–	16.000	19.000	20.393	55.964	13.857	21.778	13.000	19.536	23.132
(sig.)	0.024	0.733	–	0.000	0.000	0.000	0.000	0.001	0.000	0.002	0.000	0.000

Table 7. Chi-squared values and their asymptotic significance for the influence of science on institutional change, the types of science-driven institutional change, principles 1–9 and the results of desertification control, weighted by the influence of science, the results of desertification control and the types of science-driven institutional change
[a]IC, institutional change.

desertification control. Many researchers (e.g. Bush, 1987; Hayek, 1960; Scott, 1995) have argued that institutions or orders are bearers or carriers of dispersed knowledge, values and culture in society. The important role of knowledge and scholars in institutional change has also been emphasized in many previous studies (Hayek, 1945; North, 1990; Veblen, 1904; Yang, 2009, 2010a, 2010b, 2012; Yang and Wu, 2012). Ruttan *et al.* (Ruttan, 1978, 1984; Ruttan and Hayami, 1984) stressed the importance of technical change and social science knowledge in induced institutional change. Our study further indicates the important role of science in institutional change concerning desertification control. Although Hayek (1960) insisted that institutions and orders are spontaneous and not designed based on human rationality, the important role of science and knowledge found in this study demonstrated that, in the long run, institutional change is a spontaneous and incremental process; however, science and knowledge play important roles. Science-driven revolutionary changes can occur to a certain extent, but we cannot design an entire instructional system from the beginning. This is the dynamic process of institutional change (Baumgartner and Jones, 1993; Yang and Wu, 2012). The findings regarding desertification control, as a complex environmental management problem, provide new evidence and support for the role of science in future activities for combating desertification and other types of ecological and environmental institutional change.

However, this result does not mean that we agree with the dominant social paradigm or the positivist assumptions of science in modern science-based civilization, which posit that science and technology can provide solutions for all our problems with nature and that humankind can use science and technology to manipulate nature (Smith, 2000). We believe that science can help us resolve some of our problems, but it cannot resolve all of our problems. In addition to the results from the survey data, the relatively low significance level of the chi-squared values of the influence of science on institutional change weighted by the results of desertification control for the 25 cases in Table 7 compared with Table 3 also indicates that the role of science in desertification control and other types of environmental governance depends not only on the overall influence of science on institutional change but also on other factors, such as the types and mechanisms of science-driven institutional change. Thus, studying scientific applications in institutional change is more important than focusing on arguments about whether science is ontologically valid. Although many philosophers might be interested in the latter problem, for researchers focused on resolving the practical problems of our society to focus on the latter issue is misguided.

Methods of Scientific Measures and Types of Participant are Two Dimensions for Analyzing Types of Science-Driven Institutional Change

All earlier sciences were dedicated to the study of classifications (Gershe, 1992). The results of this study indicate that a distinction can be made among the types of institutional change by examining two dimensions, the methods of scientific measures and the types of participant involved. Although not all science-driven institutional changes fall

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into one of the aforementioned categories according to the two dimensions, the distinction sharpens our analysis and enables us to better understand science-driven institutional changes in desertification control and other types of environmental governance. In contrast with previous studies (Yang and Wu, 2012), which broadly divided knowledge-driven institutional change into two types, imposed and voluntary, in terms of the primary driving forces but did not utilize information about the scientific measures applied and the major participants involved, the new classification resolves these issues and provides an important supplementary framework for studying the types of institutional change. Furthermore, it provides more concrete policy instructions for policy makers and practitioners regarding applied scientific measures and the participants involved. In different environmental governance problems, the primary scientific measures applied and participants involved can be different; thus, the concrete types of institutional change might also be different and we must choose the most appropriate mode for the local situation to improve governance performance. Furthermore, the results indicate that the biological-control-dominant interaction (Type II) and high participation and multiple interactions (Type D) are the most effective types of science-driven institutional change in desertification control in China; this result provides concrete guidance for policy makers and practitioners in desertification control and other types of environmental governance activity.

The high chi-squared values of Types I–IV and A and B weighted by the nine principles indicated that these principles also influence the choices of the types of science-driven institutional change in desertification control. This result extended the application of these principles. Furthermore, the analysis of the chi-squared values and their significances suggested that Types A and B not only affected the influence of science on institutional change and the results of desertification control but also Types I–IV, whereas Types I–IV did not affect either the former two components or Types A and B. This result indicated that, in desertification control, the choices of Types A and B might be more important than the choices of Types I–IV.

There are Nine Working Principles for Analyzing Successful Science-Driven Institutional Change

Many studies have indicated that it is not only possible but also useful to identify a set of necessary design principles or core elements for the study of institutional arrangements and changes (Lindblom, 1977, 1990; Ostrom, 1990; Yang, 2009, 2010a; Yang and Wu, 2010, 2012; Yang, 2012). From the perspective of the science and technology used, participants, and rules influenced, we determined nine working principles to explain the success of some science-driven institutional changes. This finding reflects our endeavor to find a common set of structural elements to explain 'why particular behavior and outcomes occur in some structures and not in others' (Ostrom, 2010, p. 12). For example, this study found that, by focusing on biological controls, the science-driven institutional change of desertification control in Ordos advanced the 'Industrialize Ecological Construction and Eco-industrial Development' and created a successful 'Eco-model of Ordos' (Yin *et al.*, 2011), which met Principle 1 and improved the desertification control performance. From the field case studies, this study also found that, by considering collaboration among different types of scientific method of desertification control, Yanchi moderately satisfied Principle 3, whereas Naiman did not satisfy it because agricultural controls dominated its desertification control methods for 60 years and there was no effective collaboration among different types of method.

This study also demonstrated that these nine principles could affect the results of desertification control by affecting the overall influence of science-driven institutional change, although this effect may be smaller than the direct effect on the results of desertification control. However, the real effect and effecting mechanisms should be studied further. Furthermore, our results suggest that there is a strong relationship between the nine principles and the types of science-driven institutional change in desertification control. The nine principles could influence the types of choice and implementation mechanism of science-driven institutional change and thus influence the results of desertification control. For example, based on the results of field case studies, this study shows that, by implementing rotational grazing on natural grassland and implanting sand-fixation plants (Namujilasurong, 2002), Xinbaerhuzuo Banner moderately satisfied Principle 1 and highly satisfied Principle 3 for desertification control. These principles classified its type of science-driven institutional change as Type II and improved its desertification control performance.

Certainly, these principles may not cover all elements of successful science-driven institutional change in desertification control and are not universal for all successful science-driven institutional changes for other types of environmental governance. In particular, because of the significant complexity of diverse situations, we may not find a

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single best structure to model all successful institutional changes. These principles do embody essential and core elements that are generally associated with successful institutional change for desertification control, which provide a reference map for us to compare different structures of institutional change and to improve our future policy making and implementations of institutional changes for combating desertification and other types of environmental degradation. However, there is obviously still much more research to be performed to continue determining the factors and mechanisms that affect the process and results of institutional changes in desertification control and other types of ecological and environmental governance.

Conclusions

Desertification has been one of the greatest environmental challenges to sustainable development of our times, and science plays an important role in desertification control. This is also one of the important reasons why UNCCD (United Nations Convention to Combat Desertification) was established in 1994 to 'forge a global partnership to reverse and prevent desertification/land degradation and to mitigate the effects of drought in affected areas in order to support poverty reduction and environmental sustainability' (UNCCD, 2007) and why IPBES (Intergovernmental Platform Biodiversity and Ecosystem Service) was established in 2012 to strengthen 'the dialogue between the scientific community, governments, and other stakeholders on biodiversity and ecosystem services' (IPBES, 2014). Our study indicated that science-driven institutional change indeed improved the results of desertification control. Furthermore, the study found that the type of biological-control-dominant interaction and the type of high participation and multiple interactions were the two types with the highest desertification control performance, and successful and robust institutional changes in desertification control share the nine working principles. Although these findings did not purport to represent an exhaustive set of rules and approaches for combating desertification, they served as a theoretical framework and an empirical foundation for further research regarding science-driven institutional change and an outline for reforming the types and mechanisms of institutional change and institutionalized practices in desertification control and other ecological and environmental affairs. However, the repeatability and generalizability of these findings for other countries and other problems should be further tested in the future.

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