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Targeted control measures for improving the environment in a semiarid region of China

Qi Feng [a], Chengqi Xia [b], Wenping Yuan [c], Li Chen [d], Yafeng Wang [e], Shixiong Cao [d], *

[a] Cold and Arid Regions Environmental Engineering Research Institute, Chinese Academy of Sciences, No. 320, Donggang West Road, Lanzhou, Gansu, 730000, PR China
[b] College of Forestry, Beijing Forestry University, No. 35, Qinghuadong Road, Haidian District, Beijing, 100083, PR China
[c] College of Climate, Zhongshan University, No. 135, Xingangxi Road, Meizhu District, Guangdong, 510275, PR China
[d] School of Economics, Minzu University of China, No. 27 Zhongguancun South Street, Haidian District, Beijing, 100081, PR China
[e] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, PR China

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A B S T R A C T

Land degradation results from the interactions among multiple climate and human factors. Solving the problem requires a holistic strategy that deals with all significant factors simultaneously. However, it is difficult to solve such problems because few researchers have studied the simultaneous effects of these interactions, making it difficult to develop a truly holistic strategy. To help land managers find such a strategy, we have proposed and tested a new approach for ecological restoration in which we calculated the simultaneous contributions of multiple factors during vegetation cover change in Yan'an City, Shaanxi Province, China, from 2000 to 2016. After implementing the new approach, the vegetation cover increased by 35.7% during the study period, which is 2.3 times the rate in the rest of Shaanxi Province, where only the national Grain for Green program was implemented. The new approach accounted for 74.0% of the increased vegetation cover in the first year, and comparable values in the second and third years. Our results provide important information to guide sustainable development in China, and our approach can be adapted for use in other nations that are facing similar problems.

1. Introduction

Land degradation is an environmental issue around the world, and seriously threatens human society (D'Odorico et al., 2013). The area in which land degradation is currently occurring is the home of more than 38% of the world's population, and includes areas that are among the most sensitive to climate change and human activities (Huang et al., 2015). The area of land degradation in China is about 3.3×10^6 km^2, accounting for 34% of the total national land area, and is spread throughout 18 provinces and more than 400 counties, thereby threatening 400×10^6 people (Wang et al., 2008). With the increasing area of desertification and decreasing area of arable land, the problem of poverty is also worsening (Olukoye and Kinyamario, 2009). Due to a lack of choices, residents in these areas are often forced to engage in unsustainable activities such as deforestation, overgrazing, and land reclamation for agriculture, resulting in environmental degradation (Sietz et al., 2011). Poverty therefore leads to environmental degradation, but environmental degradation further aggravates poverty in a vicious cycle, which is called the "poverty trap" (Kates and Dasgupta, 2007). This trap makes it difficult for residents in these areas to survive because it prevents socioeconomic development (Tallis et al., 2008).

Research has shown that climate change and human activities both have significant impacts on vegetation change, and that changes in surface vegetation in turn affect the local climate (Shi et al., 2007) and human activities (Ma et al., 2014). Researchers in the natural sciences have demonstrated that climate change affects soil quality, vegetation cover, species composition, and hydrological cycles, resulting in environmental degradation (Zhou et al., 2009); at the same time, researchers in the humanities have shown that unsustainable human activities, such as overgrazing, overharvesting, and excessive groundwater exploitation, create tremendous pressure on ecosystems, causing soil erosion and aggravating land degradation (Zheng et al., 2006). However, these

* Corresponding author.
E-mail address: Shixiongcao@126.com (S. Cao).

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studies focused either on natural factors, such as meteorological factors related to climate change (Sivakumar, 2007), or on anthropogenic factors related to human activities (Olukoye and Kinyamario, 2009). There have been few studies that quantitatively analyzed the effects of interactions among multiple factors based on long-term data (Marland et al., 2003; Zhou et al., 2009; Wang et al., 2010; Feng et al., 2015). It is therefore not yet clear how the multiple factors interact and their relative importance in ecological restoration.

Researchers and restoration managers mostly focus on traditional approaches based on re-establishing ecological mechanisms or abiotic conditions that can promote restoration of a healthy and stable biotic community. Alternatively, they may be committed to developing new technologies, such as the use of biochar as a soil amendment that improves the soil quality by helping to retain water in the soil and that promotes plant growth (Marousek et al., 2017). Because the strong interactions between the biological system and the climatic environment can alter the results of environmental engineering and the subsequent ecosystem succession (Suding et al., 2004), this traditional approach appears promising, but it has a serious flaw: it ignores the importance of human impacts on the ecosystem and of the project's impacts on humans. Thus, it has typically led to losses for one component (humans) and wins for the other (the environment) rather than holistic solutions in which both components benefit. A truly effective solution must bridge the gap between the natural science and humanities research communities by developing a comprehensive approach that accounts for both human and natural factors (Cao et al., 2017). Unfortunately, such solutions have not yet been proposed and tested (Newmark et al., 2017).

To develop an effective strategy that combines both components, we proposed and tested a new approach that achieves ecological restoration through a strategy that we have named *Targeted Control Measures for Ecological Restoration*. This strategy treats a degraded ecosystem as analogous to a leaky water reservoir, and treats restoration of the degraded ecosystem as analogous to patching the holes in the reservoir so that it can refill with water. To apply this analogy in practice, we must first identify the key factors that cause ecosystem degradation (i.e., that create the holes in the reservoir), quantify their impact on the ecosystem (Cao et al., 2014; Cameron et al., 2017), and then interfere with the degradation processes (i.e., patch the holes), thereby allowing the degraded ecosystem to recover (i.e., allowing the reservoir to refill). However, ecosystems are more complex than the reservoir analogy suggests, and this makes it harder to diagnose and fix the causes of degradation. To solve this problem, we hypothesized that it would be possible to calculate the contributions of the most important factors (both natural and human) involved in degradation and recovery processes, and thereby develop *targeted control measures* to patch those specific holes in the reservoir. Though our case study was tested only in China, the concept of targeted control measures shows considerable promise for future ecological restoration research both in China and elsewhere in the world.

2. Test of Targeted Control Measures for Ecological Restoration

Yan'an City is located in the hilly loess region in northern Shaanxi Province. It covers a total area of 3.7×10^6 ha. The annual temperature averages 9.6 °C, with an extreme minimum of −11 °C and an extreme maximum of 28.2 °C. The average annual precipitation is 500 mm, of which 81.4% falls between May and October. In 2015, the city's population was 2.2×10^6, of which the rural population was 1.9×10^6. The per capita net income was 6180 RMB.

To fully understand the impacts of climate change and human activities on the evolution of ecosystems, it's helpful to choose an indicator of degradation and recovery that can be easily and reliably assessed. For degraded ecosystems, vegetation cover is one such indicator, and it has the advantage of being relatively easy to measure over large areas using satellite remote sensing. One of the most common indicators of vegetation cover is the normalized-difference vegetation index (NDVI). Because satellite-based measurements of NDVI are strongly affected by clouds, they are most suitable for dry areas with relatively low cloud cover. The changes in NDVI can then be interpreted in relation to changes in natural and human factors, for which data can be obtained from statistical yearbooks and field surveys.

In the present study, we chose the following statistical indicators, which have been shown to be associated with changes in vegetation cover in previous research (Cao et al., 2014; Feng et al., 2015):

1. rural social development indicators: population, agricultural workforce, lengths of highways and railways that have undergone greening (i.e., planting of vegetation along road slopes and in mine areas to conserve water and reduce erosion), and greening of mine areas;
2. rural economic development indicators: agricultural GDP, agricultural income, per capita income, farmland area, cultivated area, area of terraces, total grain yield, grain yield per unit area, and livestock numbers;
3. environmental policy indicators: area in which grazing is restricted, area in which forest harvesting is forbidden, afforestation area, area in which artificial grassland is created, area of farmland that is replaced with natural vegetation, and the investment in ecological projects;
4. climatic and environmental indicators: annual average temperature, annual precipitation, annual extreme temperatures, cumulative temperatures >0 °C and >10 °C, solar radiation, depth to groundwater, and abundance of surface water.

Because the units of measurement that quantify these indicators differ, it's necessary to standardize their values before combining them into an indicator system. We started by identifying the key factors (the ones with the greatest rate of change during the study period, from 2000 to 2016). We then standardized the values of these indicators using the methods of Feng et al. (2015), and calculated their contribution to the NDVI change during the same period. We used the following regression equation:

$$y_{it} = a + bx_{it} + u_{it} \tag{1}$$

where y_{it} represents the standardized NDVI value in year t (i.e., the % increase compared with the previous year) for area i, x_{it} is the value of the corresponding driving factor, u_{it} is the error term, and a and b are regression coefficients.

Because both human and natural factors contributed to the observed NDVI, we calculated the relative contributions of the most significant factors. We used the following contribution model:

$$Con_j = \frac{|SCV_j|}{\sum_1^j |SCV_j|} \tag{2}$$

where Con_j represents the contribution of driving factor j, and SCV_j is the standardized coefficient value for that factor (Feng et al., 2015).

We used the 2011 version of the STATA software (http://www.stata.com/) to perform multiple regression for equation (1), including all factors that were significantly related to the NDVI changes, and used the Breusch-Godfrey LM test to eliminate

Table 1
The relative contributions of each driving factor to the changes in NDVI from 1984 to 1999 (before implementation of the Grain for Green program) in Yan'an City, China.

	First year		Second year		Third year	
	r	Contribution (%)	r	Contribution (%)	r	Contribution (%)
Rural population	−0.801**	16.76	−0.521**	13.71	−0.247*	15.15
Rural net income	0.138*	11.08	0.529**	19.31	0.499**	12.54
Farmland area	−0.290*	11.11	−0.609**	9.49	−0.519**	11.12
Area in which forest harvesting was forbidden	0.309*	10.78	0.268*	13.89	0.330*	18.97
Greening of roads and mine areas	0.425*	5.07	0.365*	6.27	−0.096ns	13.84
Afforestation area	−0.015ns	3.79	−0.133ns	10.58	0.513*	8.51
Fruit orchard construction	0.143ns	4.35	0.412*	7.84	0.433*	10.23
Temperature	0.672**	18.05	0.577**	4.61	0.578**	4.53
Precipitation	0.725**	19.01	0.094ns	14.3	0.055ns	5.11

Notes: Significance levels: $^{**}P < 0.01$, $^{*}P < 0.05$, ns not significant.

correlated variables. The final variables retained were the annual mean temperature and precipitation, the rural population, the rural per capita net income, the cultivated area, the area of sloping land in which grazing was forbidden so as to allow natural recovery, the afforestation area, and the lengths of roads and railways and the area of mines that underwent greening.

Since 1999, China's government has implemented the national Grain for Green program, which promoted afforestation or grassland establishment in degraded farmland, in Yan'an City, but the program had an important weakness: it ignored many alternatives. As a result, 80% of the afforestation involved timber trees that could not be harvested for many years, and only 20% targeted fruit trees that would provide an ongoing source of income; in addition, little grassland was planted (Cao, 2011). The local government was troubled by the program because historical experience showed that it was not always effective. Specifically, they felt that land degradation was caused by the interactions among multiple factors and that solving the problem required a holistic strategy that went beyond the former emphasis on afforestation. To develop a more effective strategy, we proposed and tested a new approach that achieves ecological restoration through a strategy that we call *Targeted Control Measures for Ecological Restoration*.

A targeted strategy must simultaneously account for natural factors, human factors, and their interactions. To identify the parameters that were most responsible for changes in vegetation cover in the study area, we calculated the contributions of the key factors to vegetation changes from 1984 to 1999, before implementation of Grain for Green, using satellite-based measurements of NDVI to represent the vegetation status. We found that a decrease of the rural population accounted for 16.8% of the increase in NDVI, versus increases of 11.1% for an increase of rural net income, 11.1% for a decrease in the area of cultivated land, 10.8% for prohibition of forest harvesting, and 5.1% for greening of mine areas and roads from 1984 to 1999, the period before implementation of Grain for Green and our new approach (Table 1). By analyzing the responses of NDVI values in the 2nd and 3rd years after an intervention during the period from 1984 to 1999 (Table 1), we also discovered a significant time lag effect for some variables: in the 2nd year, a decrease in the rural population accounted for 13.7% of the increase in NDVI, versus 19.3% for an increase in the rural net income, and 13.9% for an increase in the area where forest harvesting was forbidden; in the 3rd year, an increase in rural net income accounted for 12.5% of the increase in NDVI, versus 11.1% for a decrease in the area of cultivated land and 19.0% for prohibition of forest harvesting. The impacts of climate change on NDVI in the current year were significant for temperature and precipitation, at 18.1 and 19.0% of the change in NDVI, respectively (Table 1). In the 2nd and 3rd years, only temperature significantly affected NDVI, with contributions of 4.6 and 4.5%, respectively.

Based on our analogy of patching the leaks in a reservoir, the government of Yan'an City identified five strategies to control degradation in addition to the strategies already being implemented under China's Grain for Green Project:

1. constructing terraces on sloping land to increase food production;
2. establishing fruit trees (instead of timber tree species) to provide an ongoing increase in rural net income;
3. forbidding grazing to allow vegetation recovery by natural forces;
4. reducing environmental pressure through urbanization (voluntary relocation of rural residents) and ecological resettlement (relocation of residents to less-degraded areas);
5. increasing soil and water conservation efforts in mine areas and on roadside slopes (greening of mine areas and roads) to protect the ecological environment.

3. Results

Satellite images showed that the total NDVI increased by 1.2% from 1984 to 1999 in Yan'an City. The NDVI had increased by 2.9% during the same time in the rest of Shaanxi Province, excluding Yan'an City. From 2000 to 2016, when the new measures were implemented, the total NDVI increased by 15.2% (from 57.9% to 66.7%) for areas of Shaanxi Province excluding Yan'an City (i.e., areas where only the Grain for Green program was implemented), versus an increase of 35.7% (from 47.9% to 65.0%) for the study area in Yan'an City where the new approach was added to Grain for Green (Fig. 1). Thus, the new approach increased NDVI at 2.3 times the rate in areas where only the Grain for Green program was implemented. The new approach accounted for 74.0% of the NDVI increase in the current year, versus 62.1% in the second year and 67.7% in the third year (Table 2).

4. Discussion

Because ecological restoration projects are intended to improve the public good, they must also promote sustainable development of human society and the project region's economy (Tallis et al., 2008). Our results suggest that the new strategy of promoting ecological restoration through socioeconomic development will prove to be a sustainable long-term strategy. Therefore, researchers should simultaneously examine the effects of environmental changes and socioeconomic changes so they can balance ecological construction with socioeconomic development (Monbiot, 2007). Because residents of project areas must be able to survive implementation of the project, socioeconomic development plays a crucial role in environmental protection; it also affects the fairness

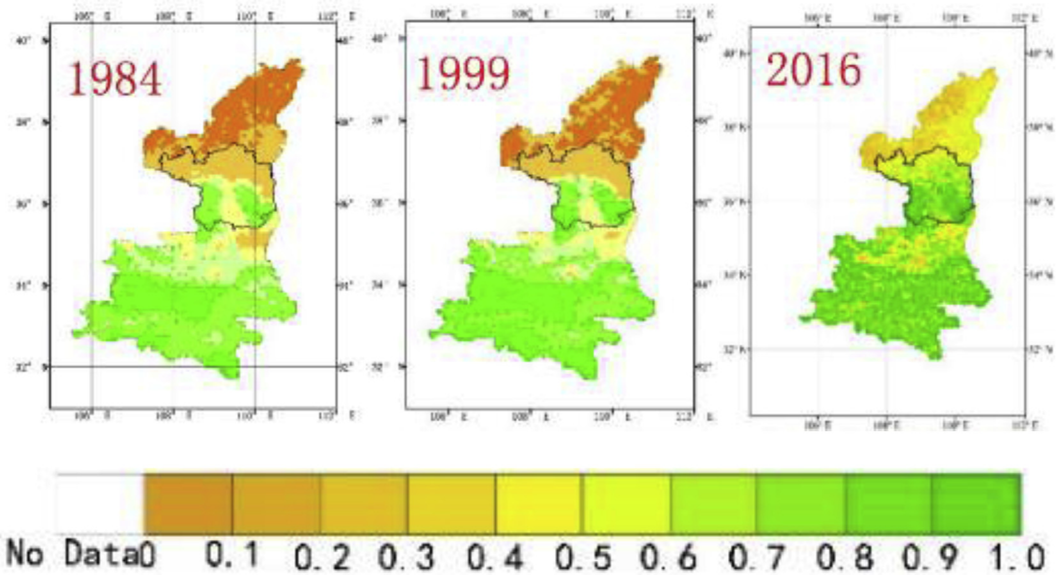

Fig. 1. NDVI in Shaanxi Province and Yan'an City (area enclosed in a black line) in 1984, 1999 (the year when the Grain for Green program was implemented throughout Shaanxi Province), and 2016. The new approach based on targeted control measures was implemented only in Yan'an City, starting in 1999. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
The contributions of each factor to the changes of NDVI since 1999 in Yan'an City, where both the Grain for Green program and the new targeted approach were implemented.

		First year		Second year		Third year	
		r	Contribution (%)	*r*	Contribution (%)	*r*	Contribution (%)
Targeted measures	Rural population	−0.743**	5.77	−0.743**	2.1	−0.743**	5.07
	Rural net income	0.331*	23.63	0.331*	30.6	0.331*	37.56
	Terrace construction	0.647**	14.62	0.647**	5.39	0.744**	3.1
	Restricted grazing area	0.628**	16.69	−0.705**	11.46	0.628**	7.89
	Greening of mine areas and roads	0.691**	13.31	0.691**	12.55	0.691**	14.03
Grain for Green	Afforestation	0.513**	12.11	0.513**	15.42	0.513**	15.3
	Fruit orchard construction	0.612**	5.62	0.612**	17.73	0.612**	5.66
Climate change	Temperature	0.678**	2.89	0.678**	2.12	0.678**	3.41
	Precipitation	0.043 ns	5.36	0.043 ns	2.63	0.043 ns	7.98

Notes: Significance levels: **$P < 0.01$, *$P < 0.05$, ns not significant.

of the distribution of benefits among people inside and outside the project area (Pagiola et al., 2005; Pywell et al., 2006), thereby making the project more acceptable to the people most strongly affected by the project.

Ecological restoration has a complex, difficult-to-measure impact on the structure and composition of future ecosystems and socioeconomic systems (Ma et al., 2013; Feng et al., 2015). The socioeconomic consequences of a project must therefore be considered even when the intent of ecological restoration is good (Gong et al., 2012). The proposed new restoration strategy appears to be suitable for a range of environmental conditions if researchers and project planners can identify the key constraints for their project area and the key driving factors responsible for vegetation change, especially in countries such as China with rapid economic growth, a dense population, and significant geographical variation (Cao, 2011). Improving the livelihood of residents of a project area and increasing their income will increase their enthusiasm for ecological restoration activities. More importantly, it will permit them to support the project in the long term instead of being forced to return to their old, unsustainable practices because they have no other ways to earn a living (Cao et al., 2009). Only in this way will it be possible for residents in ecologically fragile areas to escape the poverty trap (Cao et al., 2017). Our results show that the new approach contributed greatly to the ecological restoration, accounting for more than two-thirds of the increase in NDVI after implementation of the new approach (Table 2).

Land degradation is generally associated with the poverty trap (Cao et al., 2009). Therefore, ecological restoration projects will have direct and indirect impacts on residents of the project area. To offset these impacts, projects must provide stable and ecologically sustainable sources of employment and income to these residents. That is, all ecological restoration policies and management must account for the rights of residents of project areas to live and earn an acceptable living, which should be the highest priority (Biagini and Miller, 2013). The new approach will meet this goal, particularly since it represents a viable strategy for mitigating or escaping the poverty trap. Taking effective measures to alleviate poverty by providing sustainable development strategies can significantly improve the effects of ecological restoration (Cao et al., 2009). When implementing ecological restoration projects, policy developers and project managers must fully consider the needs of affected residents to find stable employment and sources of income after implementation is complete. This can be accomplished by providing technical training, employment assistance, and the development of green industries (Gong et al., 2012). If a project does not provide a good livelihood for local residents, any measure that protects the environment is likely to prove useless in the long term (Enfors, 2013).

Relationships among many factors are likely to exist in any region, but the relationships will be dynamic and will differ among regions (Adams et al., 2004; Wang et al., 2008). In the modern contexts of climate change, environmental degradation, and increasingly fragile ecosystems, environmental management will require more flexible solutions than traditional programs that focused on only one component of the problem, such as afforestation (Harris, 2012). To achieve this flexibility, it is first necessary to thoroughly understand the interactions between climate change, ecosystems, and human activities. Understanding which factors are most important lets managers modify their focus, thereby providing the necessary flexibility. The new approach based on holistic control of ecological restoration therefore represents a promising new area of research because it emphasizes the need for flexible solutions that focus on the most important factors. Identifying the driving forces responsible for ecosystem evolution will require new methods, such as the detection of degradation thresholds beyond which natural recovery will not be possible (Dudley et al., 2018), and will require a focus on fully understanding the local natural and human factors that will constrain or support ecological restoration. What's more, ecological restoration is a long-term (evolutionary rather than revolutionary) process, whose success cannot be ascertained in the short term. Successful ecological restoration is based on maximizing the long-term net benefits rather than maximizing a single indicator (such as forest cover) and short-term profits. This will require long-term monitoring to ensure that the correct problems have been identified and that the proposed solutions are solving those problems. In addition, the problems that were originally important may be solved and other problems may become a higher priority.

5. Conclusion

The results of our study confirm that targeted restoration can improve both the ecological environment and economic development. In addition, because the approach relies on allowing ecosystems to recover based on natural processes rather than requiring expensive interventions such as afforestation, it is potentially less expensive than traditional approaches. Future research should attempt to quantify the relative costs of the new and traditional methods. In addition, our results show measures that protect degraded ecosystems and let them recover naturally are more effective than those programs that just focus on creation of ecosystems (e.g., Green for Grain). Therefore, a targeted approach of ecological restoration represents an important breakthrough in environmental protection. Although our research is preliminary, the methodological problems solved by the new approach deserve attention. If the method is suitably modified to account for an area's unique local conditions, the new approach will help restoration managers elsewhere in the world identify the most serious problems and develop solutions that solve the problems directly and effectively. For other areas where local conditions are different from those in our study area, the new approach will also provide a theoretical basis to identify the key factors causing ecosystem degradation (i.e., the holes in the reservoir). As this approach matures, it will provide an important solution to the poverty trap both in China, and around the world.

Author contributions

S. Cao designed the research; S. Cao, C. Xia, W. Yuan, L. Chen, and Y. Wang analyzed the data; and Q. Feng, C. Xia, and S. Cao wrote the paper.

Conflicts of interest

The authors declare no conflicts of interest.

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