Current re-vegetation patterns and restoration issues in degraded geological phosphorus-rich mountain areas: A synthetic analysis of Central Yunnan, SW China

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A B S T R A C T

China has the largest area of inland geological phosphorus-rich (GPR) mountains in the world, where vegetation restoration is key to safeguarding the environment. We reviewed the published literature and collected new data in order to analyze re-vegetation patterns and the status of plant communities in central Yunnan. The aim of our analysis was to suggest future improvements to restoration strategies in GPR mountain regions. Our results showed that spontaneous recovery was the most widespread type of restoration. N-fixing species such as Coriaria nepalensis and Alnus nepalensis play a vital role in succession. In the past, monoculture tree plantation was the primary method used in afforestation activities in central Yunnan; in recent years however, several different methods of restoration have been introduced including the use of agroforestry systems. For practical restoration, we found that spontaneous recovery was capable of delivering the best results, but that during its early stages, restoration results were affected by several factors including erosion risk, the origin of propagates and environmental variation. In contrast, methods employing human-made communities performed better in their early stages, but were constrained by higher costs and vulnerability to degradation and erosion. The use of N-fixing species such as A. nepalensis and Acacia mearnsii in plantations were unsuccessful in restoring full ecosystem functions. The success of restoration activities in GPR mountain regions could be improved through the following measures: (1) developing a better understanding of the respective advantages and disadvantages of current natural and human-engineered restoration approaches; (2) elucidating the feedback mechanism between phosphorus-rich soil and species selected for restoration, especially N-fixing species; (3) introducing market incentives aimed at encouraging specific restoration activities such as agroforestry, and improving the industry value chain.

1. Introduction

China holds the second largest phosphate reserves in the world and is the biggest producer of phosphate ore (Zapata and Roy, 2004). More than 80% of China’s phosphorus (P) reserves and surface mining sites are in the mountainous southwestern region (ChinaIRR). Mining and other human disturbance leads to severe degradation of vegetation, and significant P is lost to adjacent water from geological P-rich (GPR) mountains (Das, 1999; Brown, 2005; Kuo et al., 2009; Li et al., 2014). Such erosion of P from land to water has threatened both terrestrial and aquatic ecosystems (Kuo et al., 2009; Elser and Bennett, 2011).

Central Yunnan is an important GPR mountainous area in southwest China which was the location of the earliest phosphate mining in China and now contains the largest phosphate mines in Asia (Zapata and Roy, 2004; Shang et al., 2015). The shallow and widespread P rock in this region makes surface mining attractive to the mining industry. However, this natural endowment also poses
challenges for the surrounding environment (Yang et al., 2014; Li et al., 2015a). Due to human activities, a significant amount of P is lost every year to Dianchi Lake (the largest plateau freshwater lake in China), and this has been a key contributor to algal blooms (Gao et al., 2005; Li et al., 2015b). P leaching from land to water bodies has also threatened the water safety of upstream tributaries of the Yangtze and Pearl Rivers.

Vegetation restoration is one potential solution to these problems. However, recent research has mostly focused on farmland and pasture (Sharma et al., 2007; Read, 2012; Volis, 2016). In the GPR region of Florida in the United States, research has concentrated on wetland and marsh areas but neglected mountain regions (Brown, 2005; Andrews and Broome, 2006; Jayakumar et al., 2010; Beavers et al., 2013). There is a lack of research in Asia as a whole, and very few studies have focused on the degradation and restoration of GPR mountain in China. To date, a clear overview of the re-vegetation patterns and restoration issues in China has been unavailable. Understanding the current status of plant communities, the dynamics involved in restoration and re-vegetation patterns is therefore an urgent matter (Yang et al., 2014). China has the largest inland GPR mountainous area in the world (SI 1). These mountains are facing a high P degradation risk, but targeted re-vegetation models are limited.

The objectives of this paper are, therefore, (1) to review the plant community status and vegetation restoration patterns in GPR mountains; (2) to discuss the performance of various restoration patterns in GPR mountains; (3) to suggest an intellectual framework for vegetation restoration issues in GPR mountains, SW China.

2. Materials and methods

2.1. Study areas

The central Yunnan region in China is one of the four largest sedimentary phosphate deposits in the world, alongside Khouribga in Morocco, Florida in America, and Kola in Russia. Around 15% of China’s total phosphorus ore deposits are located in the region (Zapata and Roy, 2004; Li et al., 2015c; Yan et al., 2015). The major river systems in the central Yunnan region are the Yangtze, Pearl and Red Rivers. These are connected to plateau lakes such as Dianchi Lake (the 6th largest lake in China) and Fuxian Lake (the 2nd deepest lake in China). Most of the GPR soil and vegetation in this region are located in the mountainous areas surrounding the water bodies mentioned above (24°0′–25°14′N; 102°33′–103°8′E) (Fig. 1). This is a key region for environmental protection, and almost all of the vegetation restoration research conducted around GPR areas in China were launched in this region (SI 2). We therefore chose this region for field data collection and secondary data review.

The average annual temperature in our research area is 14.6 °C, and the average annual rainfall is 925.4 mm. Central Yunnan has a subtropical semi-humid monsoon climate influenced by the southwest monsoon and westerly circulation, and the rainy season lasts from May to October. The zonal vegetation is subtropical semi-humid evergreen broadleaf forest dominated by Cyclobalanopsis, Castanopsis, and Lithocarpus of Fagaceae (Tang et al., 2010; Tang, 2015). The main soil types found in our study area were Ferralsols and Cambisols. Soil P concentrations were high and variable, the total P ranged from 0.5 to 87.4 g/kg, and available P varied from 39.6 to 748.7 mg/kg (Yan et al., 2015). In recent decades, human activities such as mining and farmland reclamation have led to severe degradation of vegetation, especially in the GPR mountainous region. Significant P has, as a result, been lost into adjacent water systems, which has threatened the environmental safety of the local and downstream river ecosystems (Gao et al., 2005).

2.2. Data collection

We collected data based on both our field investigations and published literature in order to describe plant community composition and re-vegetation patterns in the GPR mountain region. Firstly, fieldwork for GPR regions (soil total P > 1.4 mg/g) was carried out from 2014 to 2016. We recorded species name, height,
basal diameter and percent coverage, as well as re-vegetation type (natural or human-made community). Both interviews and tree rings were used to identify recovery time. Based on a species-area curve and existing published works (Tang et al., 2010), we used a 400 m² (20 m x 20 m) quadrat, and further divided the quadrat into 16 equal subplots. Random numbers were then used to generate the coordinates of the sample plots (Fig. 1c) in ArcGIS following Ranjitkar et al. (2014). Each randomly generated point represented a sample plot. We used subplots of 5-m x 5-m size and 3-m x 3-m size for shrub and herbaceous layers, respectively. Altogether there were 101 quadrats, of which we presented findings from 56 quadrats in this manuscript. Plants found in the plots were identified through examination of their physical characteristics. Nomenclature follows Flora of Yunnan (Wu, 1977). Secondly, to compare differences between GPR areas around the world as well as differences between GPR and Non-GPR areas and between re-vegetation types within central Yunnan, we reviewed published works on central Yunnan and other regions of the world. The literature survey included searching the Web of Knowledge Publications database (http://apps.isiknowledge.com/) and the China Academic Journal Network Publishing Data Base (CAJD: http://oversea.cnki.net/) until May 15th, 2016 (details of the search strategy used are given in SI 2). We compiled a database of 65 published papers dealing with the comparison of species composition and re-vegetation dynamics, and 19 published papers (51 quadrats) relevant to the comparison of plant community structure.

To identify the performance of different re-vegetation patterns, the following activities were carried out in addition to reviewing existing published work: in order to measure soil fertility properties, we collected soil (100 mm top-layer) samples from the four corners and center of each quadrat. A mixture of five soil samples taken from each sub-plot were used to measure soil characteristics. We applied oil bath K₃CrO₇ titration to determine soil carbon content and the Kjeldahl method for total soil nitrogen. Similarly, molybdenum blue photometry was used to determine total soil P after H₂SO₄-H₂O₂ digestion (Ryan et al., 2002). Water and soil erosion from GPR regions across different re-vegetation types were estimated using surface runoff, monitored at nine bounded plots (10 m x 10 m) from 2009 to 2014. This method and further data used in our analysis was previously reported in the literature, e.g. He (2015), Yan (2015) and Shi (2015). Furthermore, 12 functional traits were measured for each species within the nine bounded plots, relevant to the comparison of plant community structure. For example, 44 genera were common to both Florida, USA and central Yunnan. In the pioneer community in GPR mountainous areas, woody species richness was low and consisted of a large number of stress-tolerant genera like Lespedeza, Campylotropis, and stress-tolerant genera like Saccharum and Buddleja were similar in Shifang-Yichang and central Yunnan.

### 3. Results

#### 3.1. Plant community composition and re-vegetation patterns in GPR mountain

Restoration using natural plant communities was the most widely-distributed restoration type observed in GPR mountains in the research area. We documented a total of 27 families, 50 genera, and 57 woody species in the GPR area. We found some similarities among GPR regions regarding taxa composition (Table 1). For example, 44 genera were common to both Florida, USA and central Yunnan, including several N-fixing genera such as Anus, Desmodium, Medicago, and Myrica. N-fixing genera like Lespedeza, Campylotropis, and stress-tolerant genera like Saccharum and Buddleja were similar in Shifang-Yichang and central Yunnan.

Focusing on Central Yunnan, similar taxa composition occurred in both GPR and Non-GPR sites. Species richness was lower in GPR than in non-GPR areas. On the other hands, GPR mountains contained a higher abundance of N-fixing trees compared with non-GPR areas (Fig. 2).

In the pioneer community in GPR mountainous areas, woody species richness was low and consisted of a large number of stress-tolerant trees. Herbaceous communities were the most widely distributed community type and were dominated by species like Artemisia dubia and Saccharum rufulum. However, those herbaceous communities also suffered from invasive species like Dysphania ambrosioides and Ageratina adenophora. Shrub communities were composed of actinorhizal N-fixing species such as Coriaria nepalensis and stress-tolerant species such as Buddleja asiatica and...
Table 1
Comparing plant composition and diversity in different GPR sites.

| Vegetation regionalization | Florida USA (n = 8) | Shifang–Yichang (n = 5) | Central Yunnan (n = 19) |
|---------------------------|-------------------|-------------------------|------------------------|
|                           | Subtropical humid EBLF region in the USA | Eastern subtropical humid EBLF region in China | Western subtropical semi-humid EBLF region in China |
| No of species             | 178               | 83                      | 236                    |
| No of genera              | 148               | 69                      | 194                    |
| The similar genus with Central Yunnan |  |  |  |
| Total                     | 44                | 43                      | (20)                   |
| Woody species             | 12                | 6                       | (3)                    |
| Herbal species            | 32                | 37                      | (17)                   |
| DP of EBLF                | 3.37%             | —                       | 5.51%                  |
| N-fixation plants         | 12.36%            | 10.84%                  | 20.76%                 |
| Grass                     | 18.54%            | 8.43%                   | 10.17%                 |
| Composite plants          | 8.99%             | 27.71%                  | 11.86%                 |
| Others                    | 56.74%            | 53.01%                  | 51.69%                 |

For the results in Central Yunnan, information on plant species composition was recorded from both published papers and our field work. For the other GPR regions, information on plant species composition was obtained from extracting data from published works. (SI 3). Shifang: a city in Sichuan province China. Yichang: a city in Hubei province China. EBLF: evergreen broad-leaved forest; DP of EBLF: dominant plants of evergreen broad-leaved forest, e.g. Fagaceae, Lauraceae, Magnoliaceae, and Theaceae. (): The related genus among Central Yunnan, Shifang and Yichang, and Florida USA. —— : data deficiency. (n) indicates the number of publications for each GPR regions.

Pyracantha fortuneana. Tree communities consisted of actinorhizal N-fixing species such as *Alnus nepalensis* and coniferous species such as *Pinus yunnanensis* (Fig. 3). We found that secondary communities suffered from high levels of disturbance and invasion.

Tree planting is the primary mode for human-engineered restoration in this region. Our review of existing literature and field observations revealed that the most commonly used tree species included *Eucalyptus robusta*, *Cupressus torulosa*, and *A. nepalensis*. Shrub and herb species were not a popular choice for use in plantations, and were therefore not well-represented in the literature. The few shrub species observed included *Dodonaea viscosa* and *Lavandula angustifolia*. Similarly, herb species such as *Medicago sativa* were planted to improve soil fertility. We also found plantations of economically valuable plants such as *Paeonia suffruticosa* and *Ganoderma Lucidum* (Fig. 3). Review of the planting history of the area indicated that human-engineered restoration in the GPR mountains of central Yunnan received more attention at the end of the 20th century. Planting patterns have changed from establishing monoculture plantations to aiming at more complex mixed plantations, and recently towards agroforestry models (Fig. 4).

3.2. Performance among different re-vegetation patterns and challenges for restoration in GPR mountain areas

For spontaneous restoration, performance in the initial stages was poor, and while ideal functional recovery was achieved at later stages, this was achieved only by means of long-term succession and only under moderate conditions. In the initial stage (1–3 years), we found low soil nutrient content, infertile soil, low levels of plant diversity, and high risk of soil and water erosion. These variables showed even worse performance than in human-made plantations. However, for areas where spontaneous restoration had been ongoing for at least 25 years, soil carbon and nitrogen, community diversity, soil quality and water conservation had all significantly improved (Fig. 5). It is important to note that this level of high performance required some additional conditions, such as appropriate initial environmental settings, including the absence of steep slopes and excessively polluted lands, and the selection of adaptive pioneer species which promote the development of diversity and ecosystem services within the community. For example, diversity (as measured by Shannon Wiener’s diversity index) doubled in the *C. nepalensis* and *S. rufipilum* plantation sites during...
a 15-year period of restoration. In contrast, some other species such as *Heteropogon contortus*, *Acacia mearnsii*, brought a less positive effect (Fig. 6a and b). Furthermore, it is notable that no significant relationships were found among topsoil P contents, restoration time and models (Fig. 5c). Spontaneous restoration was found to be better than human-engineered restoration for the recovery of ecological functions in GPR mountain areas in central Yunnan. However, limitations due to the origin of propagates and environmental variation are common in the restoration process. Therefore, it is not clear under which condition spontaneous restoration will have the best results, especially in soils with excessive amounts of P.

Human-made vegetation communities have been widely used in restoration efforts. However, many problems still exist with such methods including low recovery efficiency, simple structure, vulnerability to degradation, high risk of erosion and high costs.

(1) Regarding soil recovery, higher soil carbon and nitrogen was observed during the initial stages of human-made vegetation communities. However, performance was not satisfactory during the later stages of restoration (Fig. 5a and b).

(2) Although human-made communities tended to have a higher biomass, significantly lower species diversity was observed both in the canopy, understory, and the litter layer. Communities dominated by *E. robusta* and *A. mearnsii* were almost bare under the canopy and at the soil surface (Fig. 6). Although *A. mearnsii* is a rhizobial N-fixing plant which is widely planted around the world, it cannot promote community development in GPR mountain areas. Meanwhile, several invasive species occurred in the herb layer, including *Ageratina adenophora*, *Galinsoga parviflora* and *Bidens pilosa* (Fig. 6d).

(3) Regarding species selection, there have been attempts to plant N-fixing plants in order to ameliorate the lack of available N, but only a few suitable candidate species have been identified, such as *A. mearnsii* and *A. nepalensis*. *A. nepalensis* is widely distributed throughout the mountains of southwest China and is the key species in the natural succession in GPR mountain areas. However, human-made *A. nepalensis* communities remain more vulnerable to invasive species and premature death than their naturally-occurring counterparts (Table 2, Fig. 6d).

(4) Regarding the capacity of soil and water conservation, although human-made communities perform better than spontaneous recovery during their initial stages, at later stages human-made communities often exhibit higher...
Fig. 5. Soil nutrient recovery dynamics among time and re-vegetation patterns: (a) carbon, (b) nitrogen, (c) phosphorus, (d) Shannon Wiener’s diversity index. Serious conditions: slope higher than 40° incline, mining tailings, or without any soil; Moderate conditions: slope less than 25° incline, no mining tailings, with surface soil, lower level of artificial disturbance. (e) Relationships between erosion risk through runoff and diversity dynamics. Data from published results (He, 2015; Yan, 2015; Shi, 2015).

Fig. 6. Difference among recovery time and re-vegetation patterns: (a) Shannon Wiener’s diversity index; (b) Functional diversity; (c) Max height of community; (d) Community structure and diversity among different re-vegetation patterns (recovery time > 25 years). Re-vegetation type and dominant species in each community are marked. Invasive species (see Fig. 3).
in GPR mountain areas in central Yunnan. Table 2 Some similarity among GPR sites is reported (Table 1). N-economic development, weak management, and complex terrain. Reclamation rates in this region are very low, due to depressed issues. The extent of evergreen broad-leaved forest is limited at all GPR sites. All plant communities in the GPR regions of China (Xiao et al., 2009; Yan, 2015) have suffered from invasive species such as *D. ambrosioides* and *A. adenophora*. The GPR areas of Florida, US have also suffered from invasive species such as *Imperata cylindrica* (Beavers et al., 2013). Our examination of these GPR regions show that (1) the vegetation in these areas suffer from high levels of degradation; (2) soil N and P nutrient levels are unbalanced; (3) there are significant impacts from invasive species; (4) excess high soil P content and low soil N: P ratios could result in P-toxicity for some species and hinder plants survival (Shane and Lambers, 2006; Matheny et al., 2016). These findings indicate an urgent need to deal with the issues of vegetation degradation, soil nutrition balance, and invasive species (Guariguata et al., 1995; Yan et al., 2015; Yan, 2015). Beginning at the end of the 1970s, human-engineered restoration efforts have utilized monoculture tree plantation as their primary mode of restoration. In-depth research over the past 40 years has increasingly focused attention on the use of N-fixing plants in mixed communities to boost ecosystem functions. Furthermore, rising awareness of the economic and ecological flaws of monoculture systems have prompted a reappraisal of traditional agroforestry systems and consequent efforts to revitalize such systems using modern scientific techniques. Published data indicates that tree planting can be a useful method to deal with the problems posed by P-rich areas (Delorme et al., 2000). However, there has to date been a limited amount of research targeting GPR regions, and as a result researchers and practitioners have lacked a clear understanding of issues involving geology, species selection, and vegetation management for GPR areas. In short, current restoration models have not been specifically tailored for use in GPR areas, and GPR mountain areas in particular. Increased levels of attention and effort from the scientific community are therefore required in order to design appropriate solutions for these environmentally critical areas (Xu, 2011; Frayer et al., 2014; Yan, 2015; Lu et al., 2016).

Our work has reviewed the performance and shortcomings of different re-vegetation patterns in the GPR mountains of Central Yunnan. We showed that (1) spontaneous restoration has the potential for high restoration performance under “moderate” conditions. However, the success of this method is affected by several factors including initial environmental conditions and origin of propagates. Spontaneous restoration is therefore not suitable for all circumstances and areas (Boyle, 1988; Burton et al., 2011). (2) Human-made restoration communities are vulnerable to degradation and erosion. N-fixing species planted as part of restoration efforts perform less well than those which were naturally established. In addition, human-made plantations and other structured restoration efforts require high levels of investment. For example, in the GPR region of Florida, activities including landscape renovation, restoring abandoned land to natural forest, and the construction of residential areas have been utilized for reclamation (Boyle, 1988; Brown, 2000; Andrews and Broume, 2000). Although these activities were successful, considering their high costs and the low economic progress, in addition to the complex terrain in the mountains of Yunnan, these approaches are not feasible. We therefore recommend that further research be conducted into the following aspects of restoration in GPR areas.

When considering the composition and design of the restoration community: (1) Under current re-vegetation patterns, choosing a model to match the targeted environment is essential (Fig. 7a and b). To achieve restoration goals, variables such as environmental risk and the potential of different communities for restoration across different conditions and models should be carefully evaluated. Quantitative evaluation systems should be established involving P loss, nutrient cycle, community functions, and stability in GPR mountain areas. (2) Species choice should take account of recovery conditions and stages, which are key issues of which our understanding is still limited. Proper management of different recovery stages is essential, and requires detailed information on plant species and functional types. Finally, controlling the management of key species is needed in order to maintain community functions at relatively high levels (Fig. 7c).

Restoration efforts which distribute N-fixing plants across GPR regions could enhance soil quality, including balanced levels of soil C and N, infiltration and soil particles. The adaptability of plant and microbial communities through the secretion of organic acids, enzymes, and phytohormones play a fundamental role in recovery (Chaer, 2011; Vitousek et al., 2013). Thus, the selection of appropriate species is an important step in achieving successful restoration outcomes (Ranjitkar et al., 2016). In particular, the selection of ecologically compatible N-fixing plants can drive rapid functional recovery. However, current N-fixing plantations such as *A. nepalensis* and *A. mearnsii* perform poorly in GPR mountain areas (Fig. 6). Therefore, further research is needed to examine the interaction mechanisms among P-rich environmental conditions, N-fixing plants, and other plant types, as well as the differences between N-fixing plants such as actinorhizal and rhizobial plants (Vitousek et al., 2013; Li et al., 2015d; Dötter et al., 2016).

Two important driving forces of re-vegetation require more attention. The first relates to plants and soils, which the second focuses on the need to address the social economy of mountain areas. First, regarding to the community self-organizing ability, there is involving species selection, community stability, and positive succession (Sfair et al., 2016). Second, there is a need for the provision of

| Species               | N-fixation type | Life form  | Main problems for recovery                      |
|-----------------------|----------------|------------|-----------------------------------------------|
| Alnus nepalensis       | Actinorhizal   | Tree       | Invasion, death after 20 y planting            |
| Acacia mearnsii        | Rhizobial      | Tree       | Degradation of understory layer               |
| Medicago sativa        | Rhizobial      | Herb       | Death after 2 y planting                      |
| Trifolium repens       | Rhizobial      | Herb       | Invasion, death after 2 y planting            |
| Cassia bispiculata     | Rhizobial      | Herb       | Distribution limited                          |
market incentives for vegetation restoration. Monoculture tree plantations cost about ¥0.18 to 0.27 million km⁻², which is much cheaper than reclamation costs in Florida, USA (¥0.8 million km⁻²) (Brown, 2005). However, the applicability of plantation models is limited in our research area because of lower economic returns. Similarly, although agroforestry models in principal have a high expected rate of return in GPR mountain areas, the real rates of return are limited by a lack of market incentives and policy guidance. Therefore, complex linkages need to be built between policy, market, and ecosystem services in order to introduce appropriate incentives for restoration and to make the P cycle more efficient within GPR regions (Bryan, 2013; Chazdon et al., 2015). An integrated approach that combines both the environmental and socio-economic aspects of recovery is necessary in order to fully address the key restoration issues in degraded GPR mountain areas.

5. Conclusion

The mountains of Central Yunnan contain vast areas of degraded GPR land. Our results indicate that shrub and herbaceous communities were the most widely distributed community type across the study area, and that Actinorhizal nitrogen fixing plants, e.g. Betulaceae, Coriariaceae and Rosaceae were key species in succession in GPR areas. Simple tree planting has been the primary mode for human-engineered restoration in this region, but restoration methods such as agroforestry which use complex mixed plantations to achieve better ecological and economic results are receiving increased levels of attention. Both natural and human-engineered restoration approaches suffered from the impacts of invasive species.

Spontaneous restoration has the potential for the best recovery results, but requires long-term succession and moderate conditions. In contrast, human-made restoration communities have been somewhat more successful than spontaneous restoration in their early stages, but suffer from low recovery efficiency, simple structure, vulnerability to degradation, high risk of erosion and high expense. Plantations of N-fixing species such as A. mearnsii exhibit degradation of the understory and high levels of erosion.

In order to design appropriate recovery solutions for GRP mountain areas, both field monitoring work and research under controlled conditions are needed into soil N and P balance and the relationships between different species, including N-fixing species, and phosphorus-rich soil. Furthermore, there needs to be a renewed focus on addressing both the ecological functions and financial constraints of restoration activities in GPR mountain areas.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.pld.2017.04.003.

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