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Restoration Practices Affect Alpine Meadow Ecosystem Coupling and Functions☆

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ABSTRACT

Degradation of alpine meadows on the Qinghai-Tibetan Plateau is an important issue for ecological science, policy making, and the welfare of local herders. Destruction of alpine meadows results from degeneration of vegetation and soil systems and from the mechanical decoupling of the environment, grassland, livestock, and herders and, subsequently, discordance among these subsystems. In this study, systematic integration of restoration techniques based on the grassland agroecosystems coupling theory was developed for the management and restoration of degraded alpine meadows. To test the effectiveness of these integrated restoration techniques, we conducted restoration trials that included grazing management, enclosed, fertilization, overseeding, and sward ripping by evaluating the ecosystem coupling of soil, plant and livestock, and ecosystem functions. The results of this study suggest that comprehensive restoration practices include grazing and agronomy techniques (fertilizer, overseeding, and sward ripping) that result in the greatest level of ecosystem coupling, while the single restoration practice leads to poorly coupled ecosystems. Restoration practice changes in ecosystem functionality are positively related to changes in ecosystem coupling. Our results highlight the importance of diversified restoration practices for facilitating ecological coupling and functioning in the degraded alpine meadow. The restorative scheme also bridges the gap between restoration theory and practice by providing guidelines for herders and policy makers for the urgent task of restoring degraded alpine meadows.

Introduction

Grasslands form the largest terrestrial ecosystem and, consequently, restoration of degraded natural grasslands, which amount to ~70% of total grassland area, is a global challenge (Dong et al. 2020). Recharging of rivers and aquifers, sandstorm control, and sustainability of the traditional livelihood of nomadic people are all threatened by grassland degradation (Noojipady et al. 2015).

The grasslands of the Qinghai-Tibetan Plateau (QTP), which has an average elevation of > 4 000 m, are highly sensitive to changes in land use and to environmental changes (Zhu et al. 2017). Indeed, degraded grassland on the QTP has been estimated to cover between ~4.0 and 6.0 $\times$ 10^7 ha (Dong et al. 2013). Of the total QTP grassland, according to a remote-sensing study, 6% was severely degraded, 18% was moderately degraded, and 28% was lightly degraded (Zhao et al. 2015) for a total of 52% of the grassland being degraded.

QTP grassland degradation may be due to a combination of global climate change (rainfall variability), rapidly increasing grazing pressure, rodent damage, and other factors (e.g., road building, collection of wood for fuel and herbs for medicine) (Lehnert et al. 2014; Wang et al. 2018; Dong et al. 2020). However, Hou et al. (2002) indicated that degradation of grasslands is the result of a discordance between four dominant components of the ecosystem: the environment, vegetation, animals (livestock and wildlife), and herders. For example, the discordance between vegetation and animals that occurs from overgrazing is a prevalent feature of grassland degradation worldwide and results from fluctuations in livestock-carrying capacity with seasonal changes in pasture production, livestock nutrient demand, and herbage nutritional value (Yeh et al. 2014; Zhao et al. 2018).

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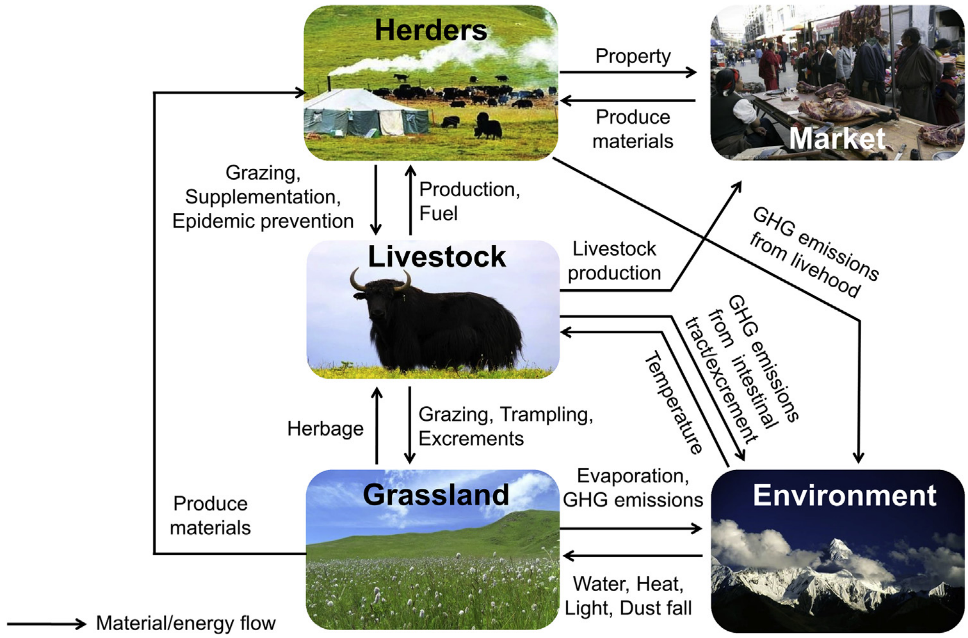

Figure 1. Material and energy flows among the environment, grassland, livestock, herders, and market of an alpine meadow ecosystem.

Theories concerning grassland restoration ecology have dramatically increased in number in the past decade (Aronson 2013; Török and Helm 2017). Mainstream theories may incorporate minimum limit theory; the laws of thermodynamics; self-design versus design theory; succession, invasion, and edge effects; and intermediate disturbance theories (Palmer et al. 2010); however, domestic restoration ecology theories lack coupling among the environment, grassland, animals, and herders. Biologists view grassland degradation as an ecosystem state arising from physical processes between the environment and grassland (Chen et al. 2017; Abdalla et al. 2018); social scientists tend to interpret the degradation as culturally determined and shaped by norms and processes of human decision making (Li et al. 2013).

The grassland agroecosystems' coupling theory was proposed by Jizhou Ren in 1980 (Lin and Hou 2004). This theory postulates that the habitat-vegetation, vegetation-animal, and animal-herder interfaces, with their four interfacing layers of pasture production, make up a complete grassland system. In general, system coupling involves two or more coupled layers under the artificial control of energy, material, and information input and output flows in larger systems, which couple to form new and superior structure-function bodies (Ren 1997; Ren and Zhu 1999; Wan and Li 2002; Ren et al. 2016). In the alpine meadow ecosystem, the vital material and energy flow also exists among the environment, grassland, livestock, herders, and the market (Fig. 1).

Although the coupling theory of grassland agroecosystems is academically accepted, there are still gaps between the theory and the practice of field techniques used for grassland restoration. On the basis of the grassland agroecosystem-coupling theory, we propose systematic integration of restoration techniques (Fig. 2) for the management and restoration of degraded alpine meadow as follows: 1) Grazing management practices involving rotational

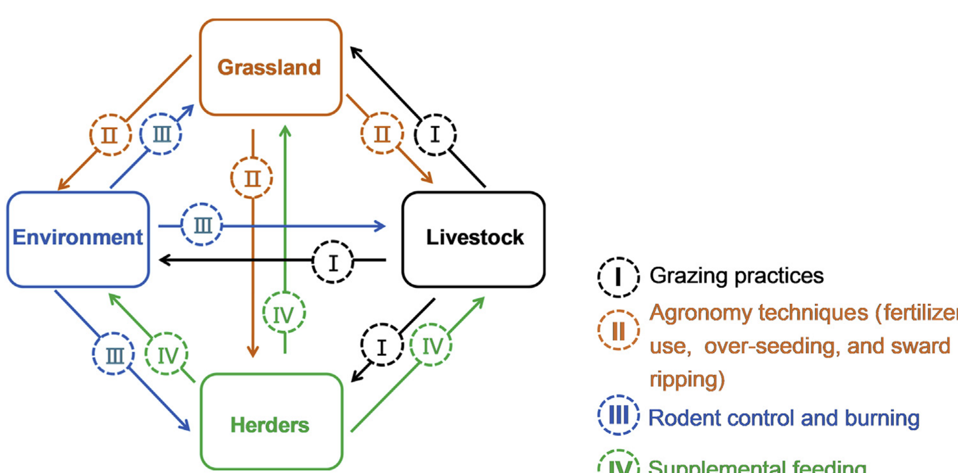

Figure 2. Schematic of the techniques used to restore a degraded alpine meadow through enhancing the systematic coupling among main components (sub ecosystems) on the Qinghai-Tibetan Plateau. *I*) Manipulation of grazing livestock, including implementation of rotational grazing, exclusion of livestock from paddock, etc. *II*) Improvement of grassland, including agronomy techniques involving overseeding, sward ripping, and control of harmful herbage, etc. *III*) Modification of abiotic and biotic environment, including the control of rodent, caterpillar and grasshopper, fertilization (element addition), etc. *IV*) Input of herders (livelihood), including supplementation feed to livestock in cold season or after daytime grazing, barn feeding, etc.

grazing, pasture resting, and/or long-term livestock exclusion are proposed; 2) agronomy techniques involving fertilization, overseeding, and sward ripping are suggested; 3) rodent control and controlled burning are included; and 4) supplemental feeding with hay during the cold season.

To test our proposed systematic integration of restoration techniques, we conducted restoration trials included grazing management, enclosed, fertilization, over-seeding, and sward ripping in a degraded alpine meadow. We evaluated the ecosystem coupling of soil, plant and livestock, and ecosystem functions (e.g., ecosystem multifunctionality). To do this, we addressed the following scientific questions: 1) effects of the systematic integration of restoration techniques on ecosystem coupling; and 2) effects of the systematic integration of restoration techniques on ecosystem functioning. We therefore predicted that diversifying restoration practices would increase ecosystem coupling and ecosystem functions more than a single restoration practice. We also predicted the relationship between ecosystem coupling and ecosystem functioning. The purpose of this paper was to bridge the conspicuous gap between restoration theory and practice and to provide practical guidelines for herders and policy makers in an effort to restore degraded alpine meadow.

Materials and Methods

Study Site

The study was conducted at the Lanzhou University's Alpine Meadow Research Station, Gansu Province (latitude 33°42'21"N; longitude 102°07'02"E; elevation ~3 500 m) in Maqu County, east QTP. Its mean annual temperature is 1.3°C, ranging from −10°C in January to 11.7°C in July, and its mean annual precipitation is ~612 mm, with precipitation occurring mainly during its short, cool summer. Its annual cloud-free solar radiation time is ~2 580 h. Its vegetation is that expected for an alpine meadow (Ren et al. 2008) and comprises sedges, grasses, and forbs. Its dominant species are *Kobresia graminifolia, E. nutans, Agrostis* spp., *Poa pratensis, Saussurea* spp., and *Anemone* spp. Its soil is primarily Mat-Cryic Cambisols (Chinese Soil Taxonomy Research Group 1995). The study site had been continuously stocked by yaks for the past 30 yr before beginning our restoration practices trials. Climate change, poor grassland management, and physical disturbance resulted in degraded conditions typical of the region. The degree of grassland degradation at our site was light to medium degree, which was based on grassland degradation index (GDI) and assessments of percent plant cover, aboveground plant production, proportion of forage, and plant height (Li et al. 2013).

Experimental Design

A relatively flat area within the study site with homogenous soil conditions was enclosed in April 2011. Sixty-four plots (replicates) of 50 × 100 m (0.5 ha) were randomly placed. The plots were randomly treated by 4 levels in the following 16 restoration treatments: 1) grazing (G), 2) enclosed (E), 3) grazing/fertilization (GF), 4) enclosed/fertilization (EF), 5) grazing/overseeding (GO), 6) enclosed/overseeding (EO), 7) grazing/sward ripping (GR), 8) enclosed/sward ripping (ER), 9) grazing/fertilization/overseeding (GFO), 10) enclosed/fertilization/overseeding (EFO), 11) grazing/fertilization/sward ripping (GFR), 12) enclosed/fertilization/sward ripping (EFR), 13) grazing/overseeding/sward ripping (GOR), 14) enclosed/overseeding/sward ripping (EOR), 15) grazing/fertilization/overseeding/sward ripping (GFOR), 16) enclosed/fertilization/overseeding/sward ripping (EFOR).

For the grazing treatment of all restoration practices, sets of four sheep were grazed in a 0.5-ha plot from July to December. The stocking rate was 8 sheep/ha. For the fertilization treatment of all restoration practices, Tibetan sheep manure was to spread to each replicate plot. The fertilization rate was 22.5 t/ha. For the overseeding treatment of all restoration practices, the high-quality native grass *Elymus nutans* was broadcast-sown to each replicate plot. The overseeding rate was 15 kg *E. nutans* seeds/ha, and seed germination was 97%. Ripping harrow was used for the sward rippling treatment of all restoration practices. The ripping harrow is made up of three rows of strong tines. The front row of tines has a 12-mm tip similar to the gutter tines, while the second and third rows have 80 × 10 mm tines with furrow cracker forks at the tip of the tines. The harrow gives a shallow till of the soil and creates a nice seedbed on the topsoil.

Sampling and Analysis

In August of each trial yr (2011–2013), one 0.5 × 0.5 m quadrat was delineated in each replicate of all treatments, and in each quadrat the height in centimeters of each plant species was measured and then cut off and bagged with all related ground litter. The litter and plant material of each species was separated, oven-dried at 65°C for 48 h, and then weighed. The aboveground biomass was taken as the sum of the individual species. The richness of the individual plant species was determined by counting the total number of plant species in each quadrat. Before analysis of nutritional quality, plant samples were sieved with a 1-mm gauge. Plant total nitrogen (TN) was determined by the selenium-catalyzed Kjeldahl method, with crude protein (CP) then calculated as 6.25 × TN. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed sequentially using an Ankom200 Fiber Analyzer (Ankom Technology, Macedon, NY).

Soil moisture was measured using a Field Scout TDR-100 instrument for time domain reflectometry (Spectrum Technologies, Plainfield, IL), in each quadrat before removing vegetation for soil sampling. Soil samples were collected in the middle of each quadrat with an auger (10-cm diameter × 10-cm depth) and were removed in successive 10-cm-deep intervals, to a depth of 40 cm. Then each 10-cm layer was separately placed in a mesh bag (with 2-mm mesh). After air-drying the soil samples for 1 month in a glasshouse, the samples from each layer were separated into root and soil subsamples. Roots were washed free of soil, oven-dried at 115°C for 48 h, and weighed. The soil subsamples were further air-dried for a month in the laboratory at room temperature and sieved through a clean 0.2-mm mesh. Soil organic carbon (SOC) was measured by the Walkey and Black method (Nelson & Sommers 1982). Soil total nitrogen (TN) released by the Kjeldahl method and soil total phosphorus (TP) were analyzed using a FIAstar 5000 flow injection analyzer (Foss Tecator, Högnäs, Sweden).

Calculations

Camargo Evenness Index

The Camargo evenness index was calculated using the biomass of each plant species in a quadrat, and the formula of Camargo (1993) is given in Equation 1. The value of the index is independent of the measurement of plant-species richness and is used as a measure of the total plant species diversity. The Camargo evenness index is calculated as follows:

$$E = 1 - \sum_{i}^{s} \sum_{j=i+1}^{s} \left({|Pi - Pj|}/_{S} \right) \quad \text{[Eq. 1]}$$

where E is the Camargo evenness index, Pi is the proportion of species i in the sample, Pj is the proportion of species j in the sample, and S is the total number of plant species in the quadrat.

Ecosystem Coupling

Data Preprocessing

In order to eliminate the influence of dimension and magnitude, the raw data need to be standardized using formulas. For the positive index (Tang 2015), see Equation 2.

$$x'_{ij} = \frac{X_{ij} - \min_{1 \le j \le n} X_{ij}}{\max_{1 \le j \le n} X_{ij} - \min_{1 \le j \le n} X_{ij}} \quad \text{[Eq. 2]}$$

while, for the negative index see Equation 3:

$$x'_{ij} = \frac{\max_{1 \le j \le n} x_{ij} - x_{ij}}{\max_{1 \le j \le n} x_{ij} - \min_{1 \le j \le n} x_{ij}} \quad \text{[Eq. 3]}$$

where, x'_{ij} and x_{ij} represent the standardized value and the original value of index j in the year i, respectively; $\max_{1<j<n} x_{ij}$ and $\min_{1<j<n} x_{ij}$ indicate the maximum and minimum value of the index j among all years, respectively.

Evaluation of Soil, Plant and Livestock

We supposed $x_1, x_2, \ldots, x_i$ represent the indexes of soil subsystem, $y_1, y_2, \ldots, y_j$ represent the indexes of the plant subsystem, and then $z_1, z_2, \ldots, z_k$ represent the indexes of the livestock subsystem.

$$s(x) = \sum_{s=1}^{i} w_s x'_s \quad \text{[Eq. 4]}$$

$$p(y) = \sum_{p=1}^{j} w_p y'_p \quad \text{[Eq. 5]}$$

$$l(z) = \sum_{l=1}^{k} w_l z'_l \quad \text{[Eq. 6]}$$

where, $s(x)$, $p(y)$, and $l(z)$ are the integration value of soil, plant, and livestock subsystem, respectively; x'_s, y'_p, and z'_l are the standardized values of xs, yp, and zl, respectively, which can be calculated by x'_{ij} described earlier; w_s, w_p and w_l are the weight of $s(x)$, $p(y)$, and $l(z)$, respectively, which can be calculated by information entropy weight.

Coupling Coordination Degree

The coupling coordination degree model is given in the following formulas:

$$D_{spl} = \sqrt{\left(\frac{[s(x) \times p(y) \times l(z)]^{\frac{1}{3}}}{\frac{[s(x) + p(y) + l(z)]}{3}}\right) \times [\alpha \times s(x) + \beta \times p(y) + \gamma \times l(z)]} \quad \text{[Eq. 7]}$$

$$D_{sp} = \sqrt{\left(\frac{[s(x) \times p(y)]^{\frac{1}{2}}}{\frac{[s(x) + p(y)]}{2}}\right) \times [\alpha \times s(x) + \beta \times p(y)]} \quad \text{[Eq. 8]}$$

$$D_{sl} = \sqrt{\left(\frac{[s(x) \times l(z)]^{\frac{1}{2}}}{\frac{[s(x) + l(z)]}{2}}\right) \times [\alpha \times s(x) + \gamma \times l(z)]} \quad \text{[Eq. 9]}$$

$$D_{pl} = \sqrt{\left(\frac{[p(y) \times l(z)]^{\frac{1}{2}}}{\frac{[p(y) + l(z)]}{2}}\right) \times [\beta \times p(y) + \gamma \times l(z)]} \quad \text{[Eq. 10]}$$

where D represents the degree of coupling coordination, and $D \in [0,1]$; α, β, and γ represent the contribution of soil, plant, and livestock, respectively.

Ecosystem Functioning

We considered four ecosystem functions and process rates: plant growth, forage quality, soil nutrient cycle, and soil carbon accumulation commonly used to assess the ecosystem multifunctionality index (Allan et al. 2015). The measured amounts of the aboveground biomass, root biomass, species richness, and plant height represented plant growth, whereas the values for the CP, NDF, and ADF of the plants represented forage quality. The values for soil moisture, soil TN, soil TP, and soil N-to-P (N:P) represented the soil nutrient cycle, with the values for soil organic carbon (SOC), soil C-to-N (C:N), and soil C-to-P (C:P) represented the soil carbon accumulation. For each function and process index, the larger the value, the greater the functioning (Byrnes et al. 2014). We calculated the quantitative ecosystem multifunctionality index using the M-index (Maestre et al. 2012). To obtain the M-index, Z-scores were first calculated for each ecosystem function and process (14 plant and soil variables) as determined for each surveyed quadrat. Raw data were normalized before calculations. A square root transformation normalized most of the variables evaluated. The Z-scores of the 14 plant and soil variables were averaged and normalized (a square-root transformation) to obtain the M-index for each replicate (quadrat). This index provides a straightforward and easily interpretable measure of the ability of different communities to sustain multiple ecosystem functions simultaneously (Byrnes et al. 2014).

Statistical Analyses

All statistical analyses were performed using R version 3.6.1 (R Development Core Team 2019), with significance levels set to $P < 0.05$. The Shapiro-Wilk goodness-of-fit test was used to examine data distributions and confirm normality. We used a mixed-effect model from the "ASREML" package (Gilmour, Gogel, Cullis, Welham, & Thompson 2015), with year as a random factor, whereas restoration practice treatment was used as fixed factors to test the effects on the ecosystem coupling, aboveground biomass, plant species richness, Camargo evenness index, forage quality index, soil carbon accumulation index, soil nutrient index, and ecosystem multifunctionality index. We conducted a Tukey's honestly significant difference test in the "AGRICOLAE" package (de Mendiburu 2014) to evaluate differences among means. In addition, we performed correlation analysis with the "GGCOR" package (Huang et al. 2019) to compute the relationships between each of the ecosystem functions, namely aboveground biomass, plant species richness, Camargo evenness index, forage quality index, soil carbon accumulation index, soil nutrient index, and ecosystem multifunctionality index and their relationships with the ecosystem coupling. All figures were constructed using Origin 2019b (Origin Lab Corporation, Northampton, MA) and "GGPLOT2" package.

Results

Ecosystem Coupling

These field trials demonstrated that ecosystem coupling was significantly ($P < 0.01$) influenced by the restoration practice treatments (Fig. 3). Grazing-combined agronomy practices led to greater ecosystem coupling coordination degree (soil-plant-livestock), reaching the highest values when grazing, fertilization, overseeding, and sward ripping were together applied for degraded alpine meadow (see Fig. 3A). Ecosystem coupling coordination degree (soil-plant-livestock) under G, GF treatments was significantly ($P < 0.01$) lower than that under other restoration treatments (see Fig. 3A). Ecosystem coupling coordination degree (soil-plant) under GFOR treatment was significantly ($P < 0.01$) higher than that under other restoration treatments (see Fig. 3B). Comparing with single-restoration-practice treatment (i.e., E, EF, EO, ER, and G), a mixture of two or more restoration practices significantly promoted ecosystem coupling coordination degree (soil-plant) (see Fig. 3B). Ecosystem coupling coordination degree (plant-livestock) under GFO restoration treatment was significantly ($P < 0.01$) lower than that under GOR and GFOR restoration treatments and was significantly ($P < 0.01$) higher than that under G and GF restoration treatments (see Fig. 3C). There were no significant ($P > 0.01$) differences among GFR, GFO, GR, and GO restoration treatments for ecosystem coupling coordination degree (plant-livestock) (see Fig. 3C). Compared with the grazing-only treatment, grazing combined with agronomy techniques led to greater ecosystem coupling coordination degree (soil-livestock) (see Fig. 3D) and the difference was significant ($P < 0.01$).

Ecosystem Functioning

These field trials demonstrated that restoration practices were significantly affected on aboveground biomass ($P = 0.0056$), plant species richness ($P < 0.001$), Camargo evenness index ($P < 0.001$), and forage quality index ($P = 0.0017$). Soil carbon accumulation index and soil nutrient index were not significantly ($P = 0.7710$, $P = 0.6190$) influenced by the restoration practice treatments (see Fig. 4). Aboveground biomass under GFOR, EFOR, GFR, and EOR restoration treatments was significantly ($P < 0.01$) higher than that under other restoration treatments (Fig. 4A). Plant species richness under GFOR, GFO, GOR, and GO restoration treatments was significantly ($P < 0.01$) higher than that under EO, GF, ER, GR, EF, and E restoration treatments (see Fig. 4B). Camargo evenness index under GFOR and GFR restoration treatments was significantly ($P < 0.01$) higher than other restoration treatments (see Fig. 4C). Forage quality index was the highest under GOR restoration treatment and was the lowest under EF restoration treatment (see Fig. 4D).

The values of ecosystem multifunctionality index were positive (more than zero) under FOR, GOR, GFR, EFOR, GFO, EFR, and EOR restoration treatments (Fig. 5). The values of ecosystem multifunctionality index were negative (< 0) under GO, EFO, GR, G, GF, ER, E, EO, and EF restoration treatments (see Fig. 5). Mixed-effect model with Tukey's HSD test showed that GFOR, EFOR, GOR, and GFR led a significant ($P < 0.01$) increase of ecosystem multifunctionality index than other restoration treatments (see Fig. 5).

The highest contribution rates for aboveground biomass, plant species richness, Camargo evenness index, forage quality index, soil carbon accumulation index, soil nutrient index, ecosystem multifunctionality, and ecosystem coupling (plant-soil) were annual

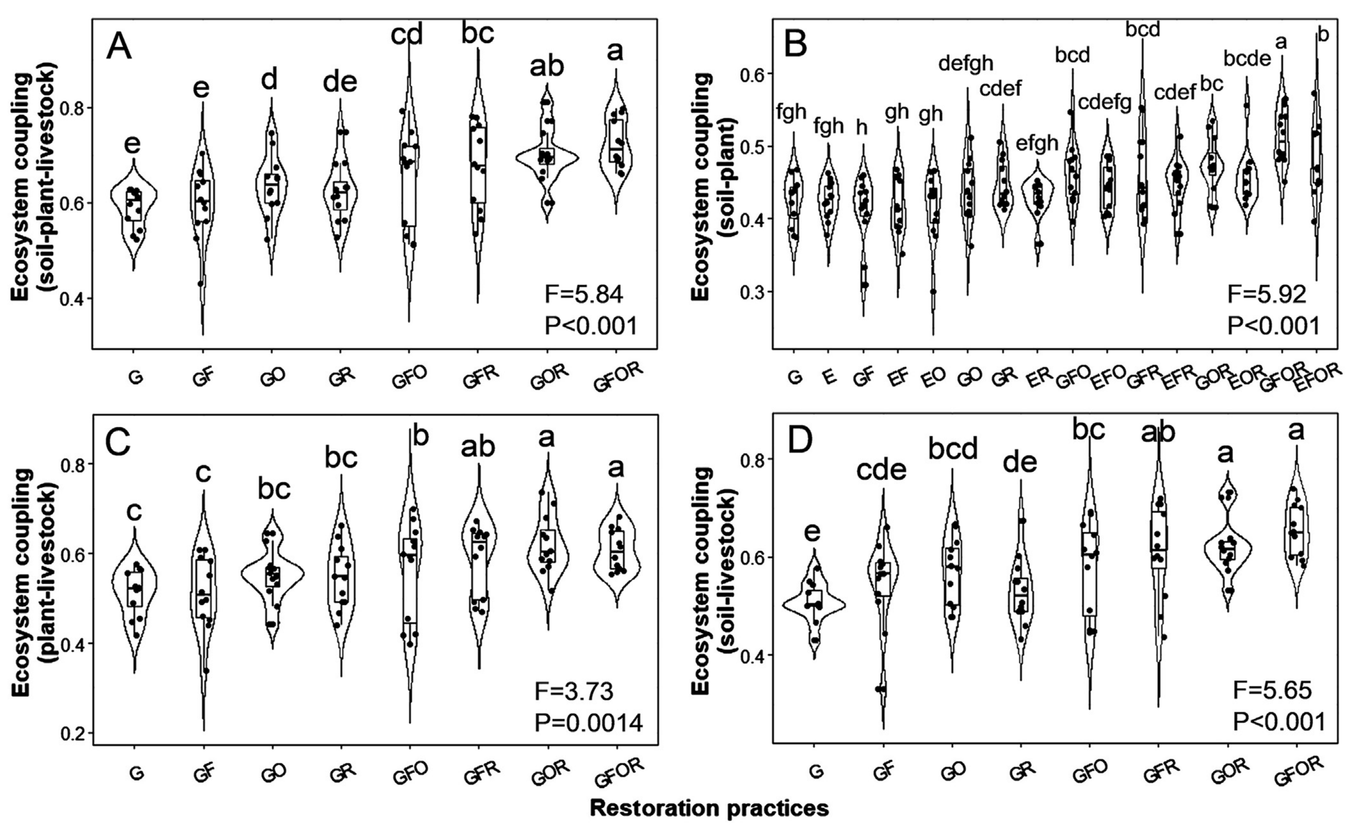

Figure 3. Effects of restoration practices on ecosystem coupling. (a) ecosystem coupling coordination degree (soil-plant-livestock); (b) ecosystem coupling coordination degree (soil-plant); (c) ecosystem coupling coordination degree (plant-livestock); and (d) ecosystem coupling coordination degree (soil-livestock). Different letters mark significant differences ($P < 0.05$) between pairs of restoration practices. G indicates grazing; E, enclosed; GF, grazing/fertilization; EF, enclosed/fertilization; GO, grazing/overseeding; EO, enclosed/overseeding; GR, grazing/sward ripping; ER, enclosed/sward ripping; GFO, grazing/fertilization/overseeding; EFO, enclosed/fertilization/overseeding; GFR, grazing/fertilization/sward ripping; EFR, enclosed/fertilization/sward ripping; GOR, grazing/overseeding/sward ripping; EOR, enclosed/overseeding/sward ripping; GFOR, grazing/fertilization/overseeding/sward ripping; EFOR, enclosed/fertilization/overseeding/sward ripping.

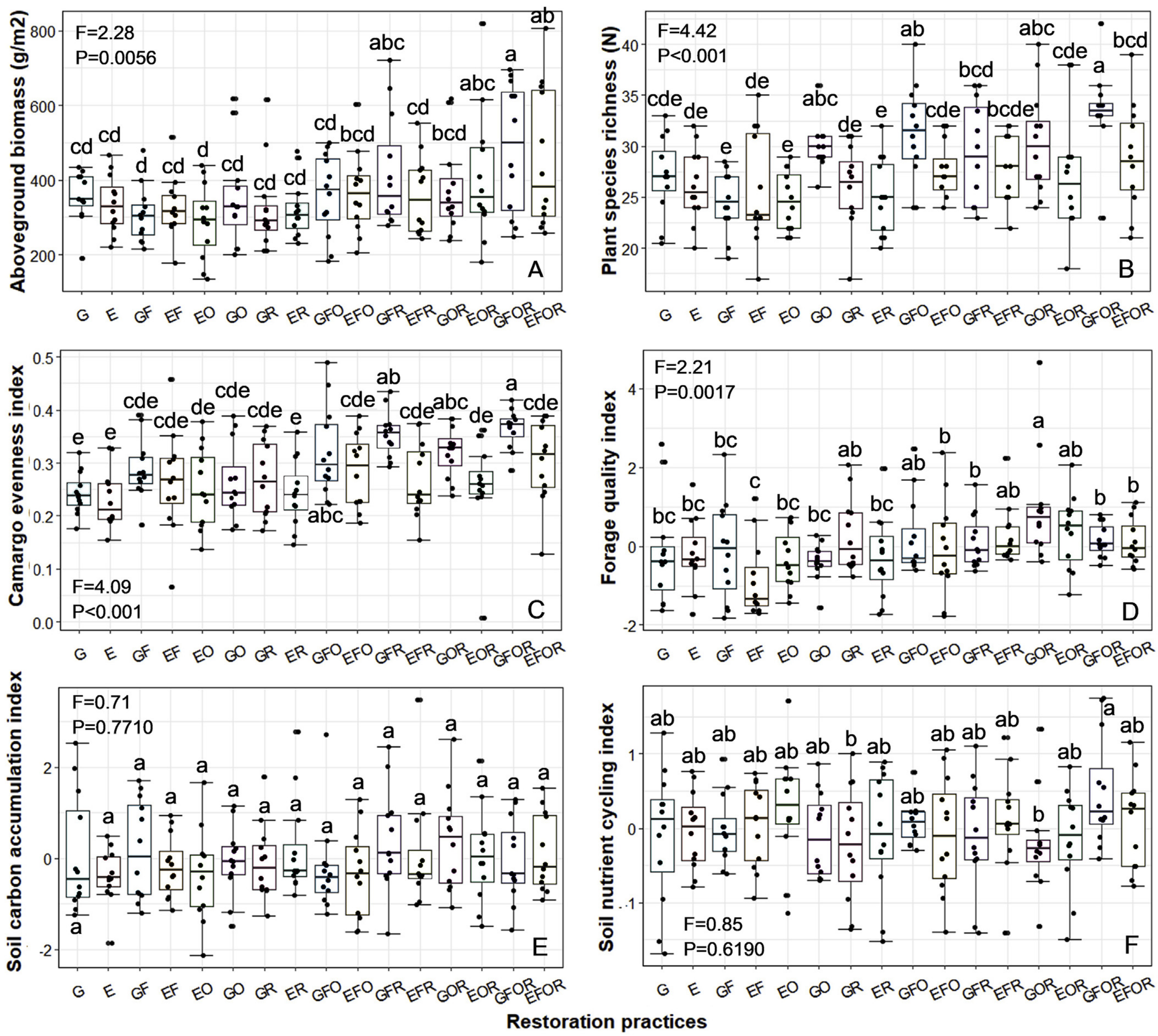

Figure 4. Restoration practices effected on (*a*) aboveground biomass, (*b*) plant species richness, (*c*) Camargo evenness index, (*d*) forage quality index, (*e*) soil carbon accumulation index, and (*f*) soil nutrient index. Different letters mark significant differences ($P < 0.05$) between pairs of restoration practices. G indicates grazing; E, enclosed; GF, grazing/fertilization; EF, enclosed/fertilization; GO, grazing/overseeding; EO, enclosed/overseeding; GR, grazing/sward ripping; ER, enclosed/sward ripping; GFO, grazing/fertilization/overseeding; EFO, enclosed/fertilization/overseeding; GFR, grazing/fertilization/sward ripping; EFR, enclosed/fertilization/sward ripping; GOR, grazing/overseeding/sward ripping; EOR, enclosed/overseeding/sward ripping; GFOR, grazing/fertilization/overseeding/sward ripping; EFOR, enclosed/fertilization/overseeding/sward ripping.

mean precipitation (45.59%), overseeding (38.01%), fertilization (34.18%), grazing (44.28%), sward ripping (58.43%), fertilization (54.43%), grazing (28.33%), and grazing (41.42%) (Fig. 6).

Relationships Between Ecosystem Coupling and Ecosystem Functioning

Relationships between ecosystem coupling and ecosystem functioning were different with different restoration practices (Figs. 7 and 8). We found that ecosystem coupling (i.e., EC_SPL, EC_SP, EC_PL and EC_SL) was significantly positively related to ecosystem multifunctionality under GFO, GFR, GOR, EOR, and EFOR restoration treatments (see Figs. 7 and 8). The correlations between ecosystem coupling (EC_SP) and ecosystem functioning (i.e., AGB, SR, EV, FQ, SC, SN, and EMF) were not significant ($P > 0.01$) under G, GO, GF, E, EF, ER, and EFO restoration treatments (see Figs. 7 and 8). Coefficients of correlation between plant species richness (SR) and ecosystem multifunctionality index (EMF) under GFOR and EFOR restoration treatments were higher than that under other restoration treatments (see Figs. 7 and 8).

Discussion

Alpine meadow is a symbiosis of the environment, grassland, animals, and herders (see Fig. 1). Degradation of alpine meadow is not only the degeneration of vegetation and soil but also the discordance of the relationships among the environment, grassland, animals, and herders (Hou et al. 2002). Restoration of alpine meadow is the process of returning to the preferred condition through promoting the systematic coupling of relationships of the environment, grassland, animals, and herders and then returning to the preferred condition through natural succession or active

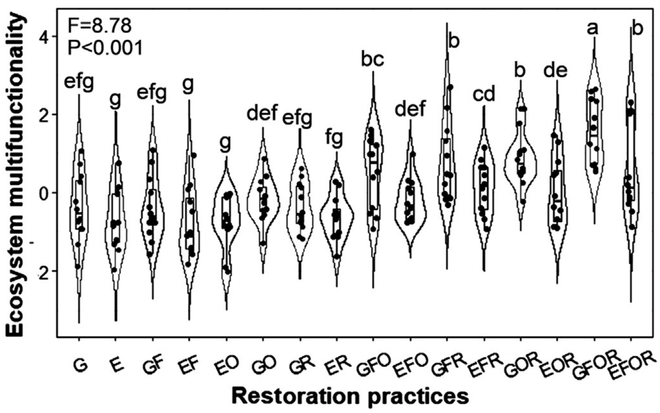

Figure 5. Effects of restoration practices on ecosystem multifunctionality index. Different letters mark significant differences ($P < 0.05$) between pairs of restoration practices. G indicates grazing; E, enclosed; GF, grazing/fertilization; EF, enclosed/fertilization; GO, grazing/overseeding; EO, enclosed/overseeding; GR, grazing/sward ripping; ER, enclosed/sward ripping; GFO, grazing/fertilization/overseeding; EFO, enclosed/fertilization/overseeding; GFR, grazing/fertilization/sward ripping; EFR, enclosed/fertilization/sward ripping; GOR, grazing/overseeding/sward ripping; EOR, enclosed/overseeding/sward ripping; GFOR, grazing/fertilization/overseeding/sward ripping; EFOR, enclosed/fertilization/overseeding/sward ripping.

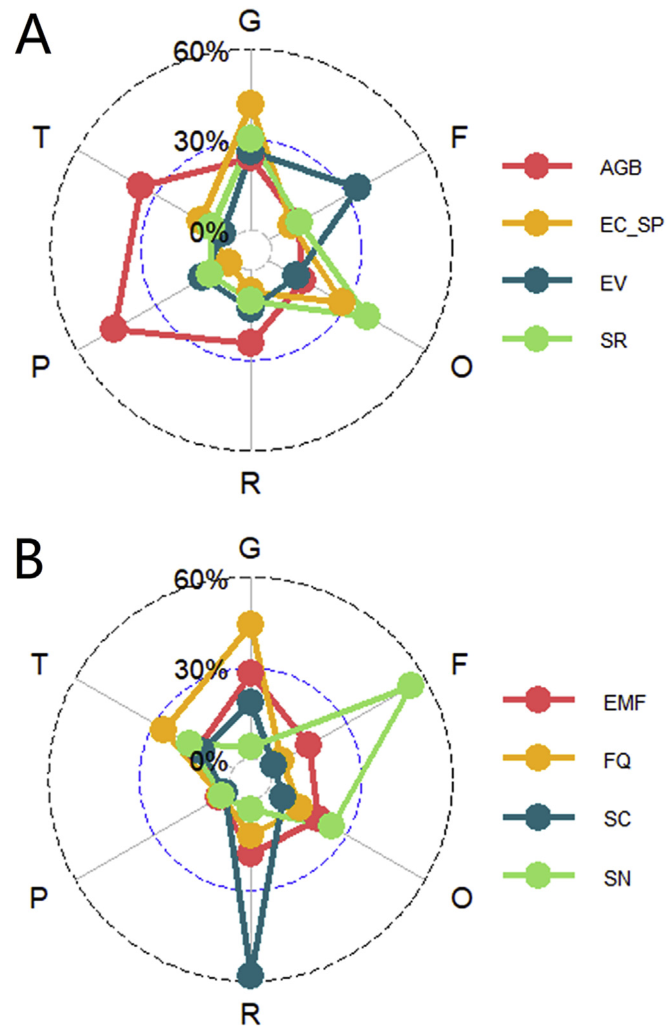

Figure 6. Contribution rate of climate factors (annual mean precipitation [*P*] and annual mean temperature [*T*]), restoration practices (grazing [*G*], fertilization [*F*], overseeding [*O*], sward ripping [*R*]) on alpine meadow ecosystem coupling (soil-plant) (EC_SP) and functions (aboveground biomass [*AGB*], plant species richness [*SR*], Camargo evenness index [*EV*], forage quality index [*FQ*], soil carbon accumulation index [*SC*], soil nutrient index [*SN*], and ecosystem multifunctionality [*EMF*]).

intervention (Ghazoul and Chazdon 2016). Establishing simple and maneuverable comprehensive indicators is the core content to evaluate the ecosystem function and health. In this paper, we used two comprehensive indicators (ecosystem coupling and ecosystem multifunctionality) to assess the effects of restoration practices on the degraded alpine meadows. An approach to investigate the interactions between multispecies communities and their environment is to analyze the degree of ecosystem coupling, which is defined as the overall strength of correlation-based associations among plants, livestock, and communities with their surrounding physicochemical environment (Risch et al. 2018; Wang et al. 2019). Ecosystem multifunctionality was defined as the ability of an ecosystem to provide multiple functions and services (Pasari et al. 2013).

Herders on the QTP use traditional methods to decide stocking rates so as to maximize the number of animals surviving each year; however, this approach often results in overgrazing, a poor outcome for grassland and animal production, and a lower, less-reliable income (Kemp et al. 2018; Michalk et al. 2019). The exclusion of livestock with mesh fencing to create large enclosures has, in recent decades, become a common grassland management strategy for reducing to the pressure of overgrazing (Wang et al. 2018). The results of this study indicated that only exclusion of livestock or exclusion combined with one agronomy practice had no improvement in ecosystem coupling and ecosystem multifunctionality (see Figs. 3–5). We also found that the determining factor for forage quality index, ecosystem multifunctionality, and ecosystem coupling (plant-soil) was grazing (see Fig. 6). A careful, tactical grazing system at suitable stocking rates can be a major tool for restoring the degraded alpine meadow. To define the sustainable stocking rates, there are two main areas where research needs to be ongoing. The first need is to determine how the grassland responds to levels of herbage biomass. Second, there must be understanding of the levels of consumption that are sustainable—the proportion of herbage on the grassland that can be eaten by livestock and not harm ecological functions and services (Michalk et al. 2019). An alpine meadow study that assessed traditional sheep stocking rates in conjunction with seasonal changes in an alpine meadow indicated that optimum stocking rates are 1.25, 3.7, 3.0, 2.65, 2.5, and 0 sheep units/ha for June, July, August, September, October, November, and December, respectively (Du et al. 2017).

Degraded alpine meadow soils have less organic matter, poorer soil nutrients including less TN and TP, and sparse vegetation (Dong et al. 2012). Fertilizer (urea and animal manure as organic fertilize), overseeding (native plant species), and sward rippling have become common restoration practices in recent years (Yang et al. 2011; Liu et al. 2016; Zhou et al. 2019). The results of this study also showed that grazing combined agronomy practices (fertilization, overseeding, and sward ripping) resulted in the greatest level of ecosystem coupling coordination degree and ecosystem functions, while the single- or double-restoration practices leaded to poorly coupled ecosystems and ecosystem functions (see Figs. 3–5). The highest values of soil-plant-livestock, soil-plant, plant-livestock, and soil-livestock coupling coordination degree that occurred at GFOR restoration treatment were 0.72, 0.51, 0.61, and 0.65, respectively (see Fig. 3). The values of ecosystem multifunctionality were 1.54, 0.84, 0.76, 0.60, 0.50, and 0.11 with GFOR, GOR, GFR, EFOR, GFO, and EFR restoration treatments (see Fig. 5). This suggests diversifying restoration practices would increase ecosystem coupling and ecosystem multifunctionality more than a single restoration practice, in agreement with our hypothesis. The comprehensive measures promote the ecosystem coupling and functions due to the complementary effect of sward rippling, overseeding, and fertilization. Perennial seed banks exist in black

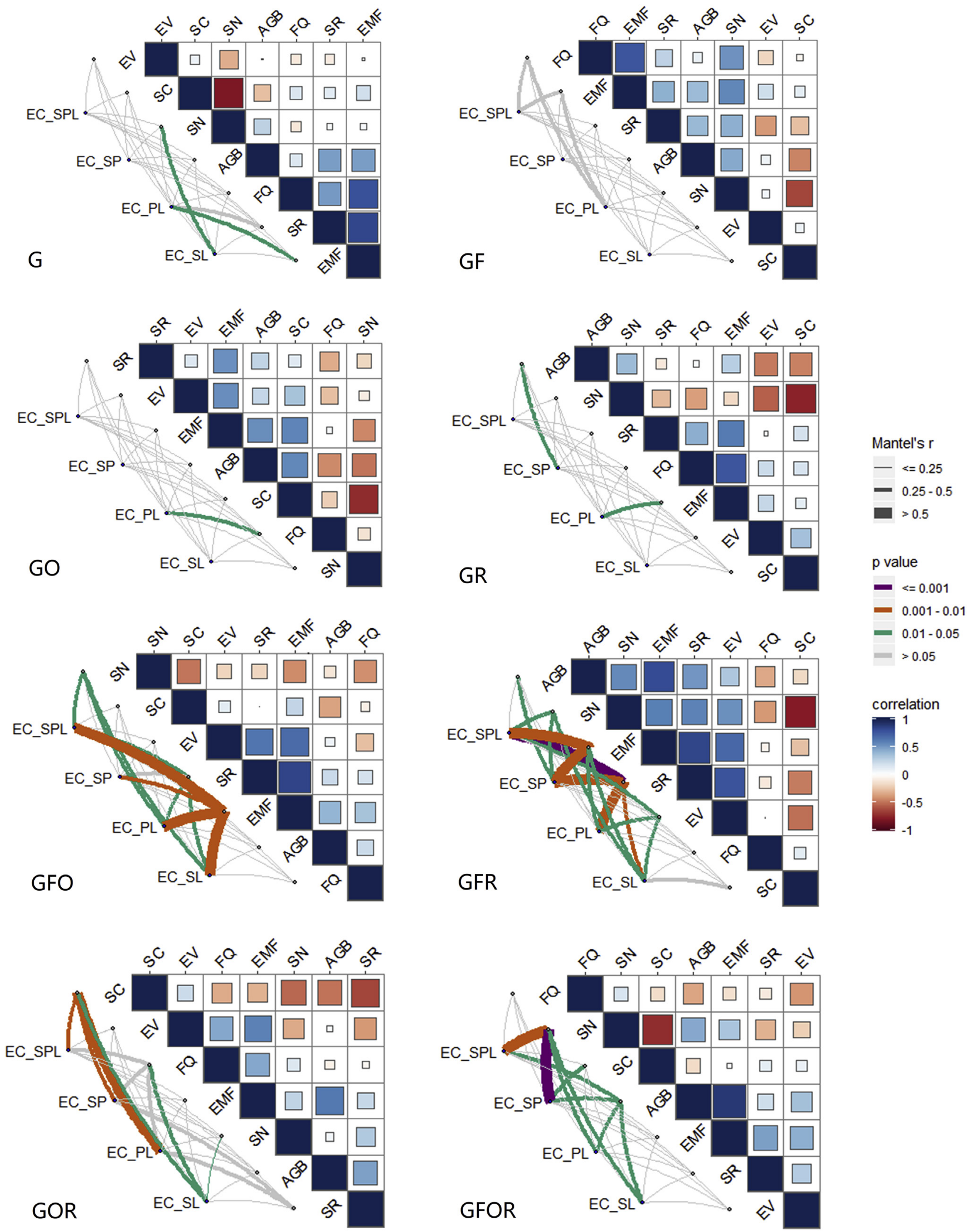

Figure 7. Effects of restoration practices on correlations between ecosystem coupling and functionality in grazed plots. Network graphs with Pearson index between constituents. AGB indicates aboveground biomass; SR, plant species richness; EV, Camargo evenness index; FQ, forage quality index; SC, soil carbon accumulation index; SN, soil nutrient index; EMF, ecosystem multifunctionality index; EC_SPL, ecosystem coupling degree (soil-plant-livestock); EC_SP, ecosystem coupling degree (soil-plant); EC_PL, ecosystem coupling degree (plant-livestock); EC_SL, ecosystem coupling degree (soil-livestock); G, grazing; GF, grazing/fertilization; GO, grazing/overseeding; GR, grazing/sward ripping; GFO, grazing/fertilization/overseeding; GFR, grazing/fertilization/sward ripping; GOR, grazing/overseeding/sward ripping; GFOR, grazing/fertilization/over-seeding/sward ripping.

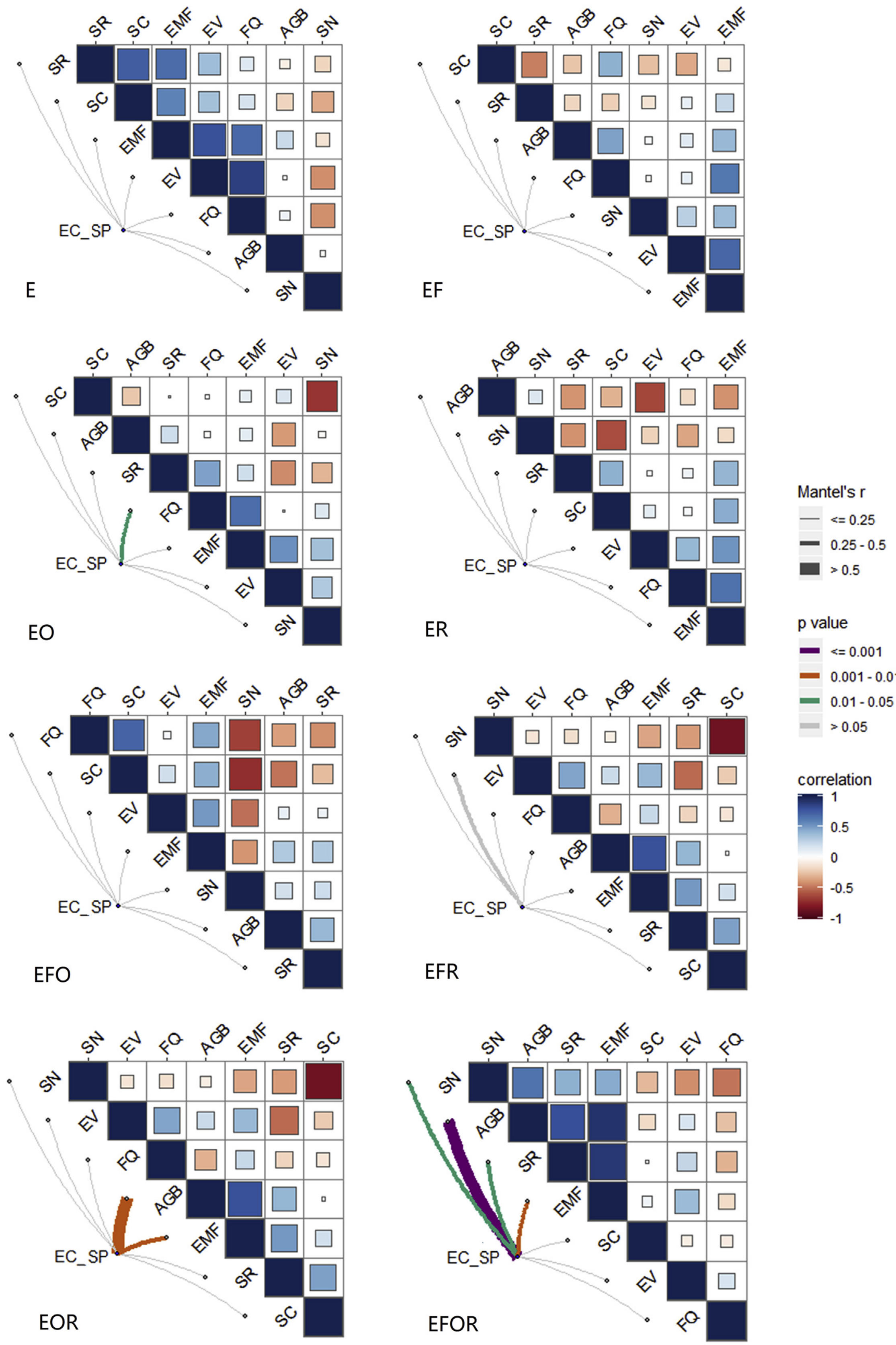

Figure 8. Effects of restoration practices on correlations between ecosystem coupling and functionality in enclosed plots. Network graphs with Pearson index between constituents. AGB indicates aboveground biomass; SR, plant species richness; EV, Camargo evenness index; FQ, forage quality index; SC, soil carbon accumulation index; SN, soil nutrient index; EMF, ecosystem multifunctionality index; EC_SP, ecosystem coupling degree (soil-plant); E, enclosed; EF, enclosed/fertilization; EO, enclosed/overseeding; ER, enclosed/sward ripping; EFO, enclosed/fertilization/overseeding; EFR, enclosed/fertilization/sward ripping; EOR, enclosed/overseeding/sward ripping; EFOR, enclosed /fertilization/overseeding/sward ripping.

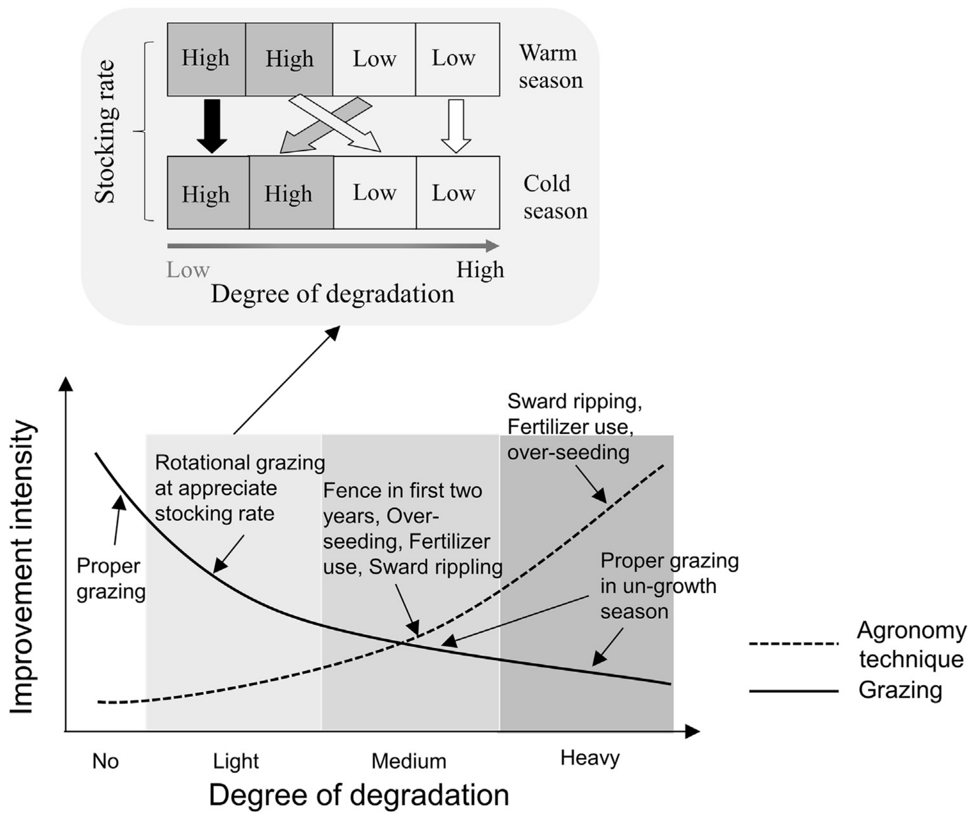

Figure 9. Conceptual model that integrates the systematic integration of restoration techniques with restoration practices (grazing management and agronomy techniques) for different stages of degraded alpine meadow.

soils, with the root biomass being twice that of the shoot biomass (Baoyin and Li 2009). Sward ripping stimulates revegetation of native plants from the underground reproductive bank (Baoyin et al. 2003). Sward ripping also increases soil porosity, which results in an increase in the water-holding capacity, improved aeration, and moisture preservation of the ripped soil (Necpálová et al. 2015). Overseeding with a new species might alter the pattern of competition among members of the original community, which, in turn, could be conducive to the formation of a new niche space and could result in increased species richness (Foster and Tilman 2003). Fertilization provides sufficient nutrient for plant growth. Adding 15 000 to 22 500 kg/ha of sheep manure is equivalent to inputting ~170 kg of N and ~75 kg of P into a hectare of soil (Bryan and Katherine 1998).

More tightly coupled ecosystem may support a wider range of functions, which could be associated with a greater efficiency in the use of resources and processing of organic matter (Morrin et al. 2017; Sobral et al. 2017; Risch et al. 2018). In addition, it is unknown how restoration practice changes in ecosystem coupling may affect ecosystem functioning. The results of this study showed that ecosystem coupling was significantly positively related to ecosystem multifunctionality under GFO, GFR, GOR, EOR, and EFOR restoration treatments (see Figs. 7 and 8). With the comprehensive restoration practices, stronger interactions among plant, soil, and livestock should lead to greater ecosystem functionality due to more efficient transfer of nutrients and energy through the system, which should result in a greater ability to withstand environmental stress (Hou et al. 2006).

Implications For Locals to Restore Degraded Alpine Meadow

Herders have adapted for centuries to climatic, social, political, and ecological pressures (Mistry and Berardi 2016). Herders are the major beneficiaries of healthy alpine meadows but also suffer the effects of degraded alpine meadows, as well as often being the cause of their degradation (Yeh et al. 2014). Our proposed system of integrated restoration techniques provides practical guidelines that should allow local herders to improve their outputs. The system of integrated restoration techniques also applied to restore the degraded alpine meadow linking with degraded stages (Fig. 9). For a lightly to moderately degraded alpine meadow (e.g., our study site), comprehensive restoration practices include grazing and agronomy techniques (fertilizer, overseeding, and sward ripping), resulting in the greatest level of ecosystem coupling and functions. When the grassland is not degraded, rotational grazing at an appropriate stocking rate can maintain its ecological function. To restore the extremely degraded alpine meadow, agronomy techniques become more effective restoration practices than grazing and exclusion of livestock.

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