Conversion of cropland into agroforestry land versus naturally-restored grassland alters soil macro-faunal diversity and trophic structure in the semi-arid agro-pasture zone of northern China Postprint

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Abstract

Restoration of cropland (termed 'Farm') after abandonment including shrubs (termed 'Shrub'), trees (termed 'Tree') and natural grassland (termed 'Grass') has become a routine process aimed to improve land productivity and control desertification. During this restoration process, soil macro-faunal diversity, and trophic structure were investigated at four types of sites (Farm, Shrub, Tree, and Grass) during growing season in the semi-arid agro-pasture zone of northern China. Results indicated that the Staphylinidae family was found to dominate at the Grass, Shrub, and Tree sites, whiles larval Pyralidae individuals were found at the Grass site only. The density of the omnivores (i.e., Formicidae family) was significantly ($P<0.05$) greater at the Grass site than at the Tree and Farm sites. The total density and richness of predator and phytophages were found to be markedly ($P<0.05$) greater at the Grass site than at the Farm site. Meanwhile, we found the taxon richness of predators was significantly ($P<0.05$) higher at the Shrub site than at the Farm and Tree sites. Compared with the Farm and afforested Shrub/Tree sites, the Grass site had greater density, taxon richness, and Shannon index ($P<0.05$). In conclusion, natural restoration of abandoned croplands toward grassland was an effective strategy relative to artificial afforestation for improvement of soil biological diversity. Moreover, planting shrub is a preferable measure in abandoned croplands for land development in the semi-arid agro-pasture zone of northern China.

Full Text

Preamble

Conversion of Cropland into Agroforestry versus Naturally-Restored Grassland Alters Macro-Faunal Diversity and Trophic Structure in the Semi-Arid Agro-Pasture Zone of Northern China

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Abstract

Restoration of abandoned cropland (termed 'Farm') through shrub planting (termed 'Shrub'), tree planting (termed 'Tree'), and natural grassland recovery (termed 'Grass') has become a common practice aimed at improving land productivity and controlling desertification. This study investigated soil macrofaunal diversity and trophic structure across these four land-use types during the growing season in the semi-arid agro-pasture zone of northern China. Results indicated that the Staphylinidae family dominated at the Grass, Shrub, and Tree sites, while larval Pyralidae individuals were found exclusively at the Grass site. The density of omnivores (i.e., Formicidae family) was significantly greater ($P<0.05$) at the Grass site compared to the Tree and Farm sites. Total density and richness of predators and phytophages were markedly higher ($P<0.05$) at the Grass site than at the Farm site. Meanwhile, predator taxon richness was significantly higher ($P<0.05$) at the Shrub site than at the Farm and Tree sites. Compared with the Farm and afforested Shrub/Tree sites, the Grass site exhibited greater density, taxon richness, and Shannon index ($P<0.05$). In conclusion, natural restoration of abandoned croplands to grassland was more effective than artificial afforestation for improving soil biological diversity. Moreover, shrub planting represents a preferable measure for land development in abandoned croplands within the semi-arid agro-pasture zone of northern China.

Keywords: abandoned cropland; agro-pasture zone; community diversity; land restoration; soil macrofauna

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1 Introduction

In the arid and semi-arid agro-pasture zone of northern China, more than half of the pasture area has been cultivated for economic crops in recent years (Zhao et al., 2007). Such grassland cultivation has made these ecosystems more susceptible to degradation through topsoil erosion, leading to significant biodiversity loss and subsequent desertification (Su et al., 2004). To protect and improve degraded sandy grassland ecosystems, local governments and residents have typically applied two recovery practices: (1) natural restoration of abandoned croplands under exclosure management, and (2) artificial afforestation of abandoned croplands through shrub and/or tree plantations (Thomas et al., 2004; Wang et al., 2010; Liu et al., 2014).

Given the importance of these restoration practices, numerous studies have examined their effectiveness on soil-vegetation systems following conversion of cropland to naturally restored grassland and agroforestry systems (Zhao et al., 2010; Hu et al., 2016). Since the 1950s, the U.S. government has implemented land acreage reduction programs to protect soil resources (Ericksen and Collins, 1985). In China, the first such practices were initiated in 1999 in Sichuan, Shanxi, and Gansu provinces to restore abandoned croplands to grassland and agroforestry systems (Li, 2002). This conversion process has been reported to alter plant cover and soil physical and chemical parameters over time (Hou and Zhang, 2002; Yang et al., 2006; Liu, 2009), playing an important role in the recovery of degraded arid ecosystems and informing related land management practices (Zhao et al., 2010).

For example, Thomas et al. (2004) found rapid recolonization of soil macrofauna in former rice fields after cultivation abandonment. Liu et al. (2013a) demonstrated that naturally restored grassland under livestock exclusion could enhance soil macro-faunal assemblages and improve biodiversity relative to cultivated croplands. Takeda and Abe (2001) and Liu et al. (2014) reported that artificially afforested plantations could provide suitable living conditions resulting in complex soil macro-faunal community structures. Overall, abiotic factors modulated by afforested plantations with different life forms (i.e., shrubs and trees) could dictate varying spatial and temporal activities of soil animals (Whitford, 2000; Doblas-Miranda et al., 2009; Liu et al., 2013b). However, changes in soil macro-faunal diversity and trophic structure in response to different conversion practices in the semi-arid agro-pasture zone of northern China remain largely unknown.

Soil fauna is ecologically important in many aspects (Liu et al., 2013b). These organisms act as pollinators and important components of food chains and nutrient cycles, and they can alter soil structure and fertility in arid and semi-arid regions (Lobry de Bruyn, 1999). Moreover, soil macro-arthropods have limited migration ability and relatively small home ranges, making them very sensitive to changes in soil environments (Dennis, 2003; Zhao and Liu, 2013). Any changes in soil environment caused by land management practices can significantly affect soil communities (Doblas-Miranda et al., 2009; Zhao and Liu, 2013). Furthermore, interactions between belowground and aboveground ecosystems can considerably influence community- and ecosystem-level processes during the recovery of degraded arid ecosystems (Wardle et al., 2004). In northern China’ s agro-pasture zone, land management practices frequently occur, including cultivation of grassland into croplands, shrub/tree afforestation in abandoned croplands, and allowance of natural restoration of abandoned croplands (Liu, 2009). Therefore, assessing the effects of land management practices involving conversion from cropland to agroforestry and grassland on soil faunal communities is essential (Zhao et al., 2010).

The aims of this study were to: (1) determine soil macro-faunal community composition, density, and diversity together with trophic structure under different land management practices involving conversion from cropland to agroforestry systems and naturally restored grassland; and (2) determine the relationship between soil macro-faunal community structures and soil properties in the semi-arid agro-pasture zone of northern China. Two hypotheses were proposed: (1) conversion from cropland to agroforestry systems and grassland could increase soil macro-faunal activity, abundance, and diversity; and (2) agroforestry practices through tree/shrub plantations could facilitate greater soil macro-faunal diversity relative to naturally restored grassland.

2.1 Study Area

The study was conducted at the Naiman Desertification Research Station (42°55 N, 120°42 E; 360 m a.s.l.), Chinese Academy of Sciences, located in the southwestern part of the Horqin Sandy Land in Inner Mongolia Autonomous Region, northern China. Crop production (e.g., corn, wheat, and watermelon) was the main land use during the short growing season (May to September). However, large areas of these cultivated grasslands have become moderately to seriously desertified after abandonment (Zhao et al., 2010), as decreased productivity was a primary motive for farmers to abandon land. To protect soil resources and control desertification, local farmers have restored these abandoned lands naturally through native vegetation, shrubs, and/or trees for nearly half a century (Wang et al., 2010). Main plant species used for afforestation included trees (*Populus simonii* and *Pinus sylvestris*) and sub-shrubs/shrubs (*Caragana microphylla*, *Salix gordeivii*, *Periploca sepium*, and *Artemisia halodendron*) (Zhao et al., 2010).

The region has a continental semi-arid climate with strong winds, dry winters and springs, comparatively rain-rich summers, and short, cool autumns. Mean annual precipitation is 366 mm, with 70%-80% falling during the summer growing season, and annual potential evaporation is 1935 mm. The annual mean temperature is 6.8°C, with a maximum mean monthly temperature of 21.9°C in July and a minimum of -14.7°C in January. Annual mean wind velocity ranges from 3.4 to 4.1 m/s. Regional soils are classified as degraded sandy chestnut soils according to the Chinese soil classification system, mostly equivalent to

Orthi-sandic Entisols of sand origin according to the FAO-UNESCO system (Zhao et al., 2007).

2.2 Experimental Design

Four land cover types were selected: (1) two replicate croplands with maize (*Zea mays*) monoculture for five years served as control sites (termed 'Farm'); (2) two nearby replicate abandoned maize croplands under exclosure for natural restoration for 16 years served as naturally restored grassland (termed 'Grass'); (3) two nearby replicate abandoned maize croplands afforested with *Populus simonii* woodlands served as artificial agroforestry lands (termed 'Tree'); and (4) two replicate abandoned maize croplands afforested with *Periploca sepium* shrublands for 20 years served as artificial agroforestry lands (termed 'Shrub'). Each site type comprised an area of 0.5–3.0 hm^2. Basic vegetation characteristics are provided in Table 1 .

From late July to early August 2009, five sampling points were randomly selected at each replicate site, with one 1 m × 1 m quadrat placed at the center of each point. This summer sampling period represented the growing season when plant biomass and soil arthropod activity abundances are greatest (Luo et al., 2016; Zhao et al., 2014). In each quadrat, a 30 cm × 30 cm × 30 cm soil sample was excavated and all macro-organisms were recovered by hand-sorting to investigate soil macro-faunal community structure. Additional soil samples from 0–30 cm depth were collected using a cylindrical 200-cm^3 stainless steel auger for physical-chemical property analysis. Each composite sample was obtained by mixing five subsamples from five locations within each quadrat. A total of 80 samples were collected for soil arthropod community and abiotic analysis per site (2 samples × 5 quadrats × 2 replicate sites × 4 land management types).

2.3 Data Collection

Soil macro-fauna samples were stored in 75% alcohol in the field and transported to the laboratory for identification to order and/or family level using keys from Yin (2001) and Zheng and Gui (1999). Specimens were classified into taxonomic groups based on morphological features under a binocular magnifying glass (40×). The taxonomic assemblage was further classified into four trophic groups—predators (Pr), phytophages (Ph), saprophages (Sa), and omnivores (Om)—based on feeding lifestyle as described by Doblas-Miranda et al. (2007).

Soil samples for physical-chemical analysis were sieved through a 2-mm mesh to remove plant material and debris. Approximately 5 g of each sieved sample was oven-dried to determine soil water content (%). Another portion (~20 g) was air-dried for chemical property analysis. Soil pH and electrical conductivity (EC, µs/cm) were measured in 1:1 (v/v) soil-water solution and 1:5 (v/v) aqueous extract, respectively. Soil organic carbon (SOC, g/kg) was measured using the K Cr O -H SO oxidation method (Walkley and Black, 1934), and soil total nitrogen (TN, g/kg) was measured by the Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy). Soil temperature (ST, °C) at 30 cm depth was measured during the experimental period using a portable thermometer with conductivity wires (Sato Keiryoki Mfg Co. Ltd., Japan). Soil properties at each site are summarized in Table 2 .

2.4 Data Analysis

Within each replicate, specimens from the five sampling points were pooled as one sample for two reasons: (1) no significant differences in soil macro-faunal density were observed among the five points, and (2) to enrich data for multivariate analysis of variance. Adult and larval groups were recorded separately due to their different ecological roles (Swift et al., 1979). The density of each taxonomic group was determined per site, and total density (individuals/m^2), taxonomic richness (total number of taxonomic groups per square meter), and Shannon index (H) were calculated, where x is the number of individuals in group category i, and P is the proportion of total individuals belonging to group category i.

Redundancy analysis (RDA) was used to examine how abiotic factors (ST, SWC, pH, EC, SOC, and TN) affected the distribution of faunal groups (Leps and Smilauer, 2003). Data were first analyzed by detrended correspondence analysis (DCA) using CANOCO software version 4.5 (Microcomputer Power, Ithaca, NY), which suggested RDA as appropriate (gradient length <4 for soil macro-faunal communities). RDA correlated each faunal group with environmental variables by selecting linear combinations that minimized residual sum of squares (Liu et al., 2016). Monte Carlo permutation procedures (499 permutations under reduced model) tested significance ($P<0.05$) of selected soil properties.

All statistical analyses were performed using SPSS version 15.0 for Windows (SPSS Inc., Chicago, IL). Post-hoc tests with multiple comparisons (Fisher’ s Least Significant Difference) and analysis of variance (ANOVA) clarified statistical differences among sites. Normality and homogeneity of variances were tested before parametric analyses. Statistical significance was assigned at $P<0.05$ for all tests.

3.1 Composition and Density of Taxonomical Groups of Soil Macro-Faunal Community

A total of 45 taxonomic groups from 8 orders and 39 families were collected across all sites during the study period (Table 3). The Farm, Shrub, Tree, and Grass sites had 11, 23, 10, and 35 taxonomic groups, respectively. The overall assemblage was dominated by the family Staphylinidae and larval Melolonthidae (comprising 17.72% of Coleoptera and 15.02% of the total community, respectively), along with the family Formicidae (Hymenoptera, 21.92%), which together accounted for 54.66% of total individuals. Nineteen of the 45 taxonomic groups represented >1% of total individuals, while the remaining 26 groups comprised only 11.41% of the total.

Within the soil macro-faunal assemblage, Staphylinidae density was remarkably greater at the Grass site compared to the Shrub and Tree sites, with no individuals collected at the Farm site (Table 3). Larval Melolonthidae density was considerably greater at the Grass site compared to the Tree and Farm sites. Formicidae density was significantly greater ($P<0.05$) at the Grass site than at the Tree and Farm sites, with intermediate values at the Shrub site. A similar pattern was observed for larval Tenebrionidae density, following the order Grass > Shrub > Farm = Tree. Numerous larval Pyralidae individuals were found exclusively at the Grass site.

3.2 Taxon Density and Richness of Functional Groups of Soil Macro-Faunal Community

One taxonomic group (family Formicidae) was identified as omnivores, yielding results identical to those mentioned above. Two taxonomic groups (larval Asilidae and larval Therevidae) were identified as saprophages, with 1, 2, 3, and 3 individuals observed at the Farm, Shrub, Tree, and Grass sites, respectively. No significant differences ($P>0.05$) in saprophage density or taxon richness were observed among the four sites.

Compared to the Farm site, total predator and phytophage densities were markedly greater ($P<0.05$) at the Grass site, while no significant differences ($P>0.05$) were found among the Farm, Shrub, and Tree sites (Fig. 1 [Figure 1: see original paper]). Similarly, phytophage taxon richness was markedly greater ($P<0.05$) at the Grass site compared to the Farm site, with no significant differences among the Farm, Shrub, and Tree sites. However, predator taxon richness was significantly greater ($P<0.05$) at the Grass and Shrub sites compared to the Farm and Tree sites, with no significant difference between the latter two.

3.3 Community Indices of Soil Macro-Faunal Community

Conversion of cropland to agroforestry and grassland sites significantly affected soil macro-faunal density and diversity indices ($P<0.05$) (Fig. 2 [Figure 2: see original paper]). The Grass site exhibited markedly greater density, taxon richness, and Shannon index compared to the Farm and Shrub sites ($P<0.05$). However, no significant differences ($P>0.05$) in these three community indices were observed among the Farm, Shrub, and Tree sites.

3.4 Contribution of Soil Properties to Soil Macro-Faunal Community Structure

RDA was performed to determine the main factors affecting soil macro-faunal community structure following cropland conversion to agroforestry land and grassland (Fig. 3 [Figure 3: see original paper]). Axes 1 and 2 accounted for 70.1% and 23.9% of overall variance in faunal group data, respectively, totaling

94.0% of the total variance. The cumulative species-environment relationship for axes 1 and 2 was 96.3%, indicating that most variance in faunal group data could be attributed to soil physical-chemical properties. Species-environment correlations for both axes exceeded 0.98, indicating strong correlation between faunal group data and environmental parameters. Monte Carlo significance tests revealed that both the first axis ($F=4.69$, $P=0.04$) and all axes combined ($F=17.02$, $P=0.02$) explained significant variation in the data.

Figure 3 illustrates variable values and interactions, with arrow length indicating the variance explained by each factor and arrow direction showing increasing concentration. Cumulative canonical coefficients and interrelated correlations for axes 1 and 2 indicated that total soil nitrogen ($r=0.647$, $P<0.01$), organic carbon ($r=0.522$, $P<0.05$), and soil pH ($r=0.508$, $P<0.05$) had the greatest influence on faunal community structure. This suggests that variability in soil macro-faunal density along the first and second axes was driven by soil total nitrogen, organic carbon, and pH.

4 Discussion

In the arid and semi-arid agro-pasture zone of northern China, land management practices involving restoration of cropland to agroforestry land and grassland are widely recognized by local governments and residents as means to improve degraded ecosystem recovery and reverse desertification for land development (Ma, 2003; Zhao et al., 2010). These management practices alter environmental conditions that strongly influence soil arthropod composition and density distribution (Callaham et al., 2006; Zhao and Liu, 2013). The present study found abundant Staphylinidae at the Grass, Shrub, and Tree sites, but larval Pyralidae only at the Grass site. Moreover, considerably greater numbers of larval Melolonthidae, Tenebrionidae, and Formicidae were found at the Grass site. These findings align with Liu et al. (2013a, 2014), who reported diverse and specific taxa at Grass sites under grazing exclusion through natural restoration compared to Farm and/or Shrub sites. The RDA biplot confirmed that these four families (larval Pyralidae, larval Melolonthidae, larval Tenebrionidae, and Formicidae) preferred naturally restored grassland from abandoned croplands.

These family-specific responses to microhabitat preferences could serve as reliable bioindicators of environmental change resulting from land use alterations (Heino and Soininen, 2007; Vieira et al., 2012). The increased numbers of these taxa at the Grass site correlated significantly with diverse food resources provided by recovered vegetation cover and herbaceous diversity, similar to findings by Liu et al. (2014). This likely reflects the Grass site offering more niche space compared to the mono-microhabitats at the Farm site, thereby diversifying living conditions for these specific taxa according to Tilman's resource competition theory (Tilman, 1981).

Conversion of cropland to agroforestry land and grassland affected trophic-group composition, reflecting changes in resource availability within each habitat (Wardhaugh et al., 2012). Greater predator density and taxon richness at the Grass site were determined by phytophage arthropod density and richness, which serve as potential prey and are strongly related to altered abiotic conditions (Liu et al., 2015b). Zhao and Liu (2013) and Liu et al. (2016) found that afforested shrubland created diverse herbaceous vegetation and improved soil properties, forming attractive niches that enhanced predator-dwelling family diversity. Similarly, the greatest omnivore abundance (i.e., Formicidae) at the Grass site correlated with recovered vegetation cover and herbaceous diversity (Liu et al., 2014).

Taxon richness and Shannon index illuminated shifts in taxonomic and trophic composition following cropland conversion to afforested plantation and naturally restored grassland. This finding was inconsistent with our first hypothesis and with Thomas et al. (2004), who reported greater species richness in recent ex-rice fields (2 years) compared to natural grassland. However, it aligned with previous studies on other ecosystems where human-induced changes in soil pH, moisture, nutrients, and resource availability structured soil faunal communities (Huhta and Hanninen, 2001; Byrne et al., 2008; Hanel, 2010). Multivariate analysis revealed that community structure changes were largely mediated by environmental parameters (soil organic carbon, total nitrogen, and herbaceous vegetation). These results explained 94% of arthropod community shifts, with soil physical-chemical variables (soil temperature, water content, total nitrogen, organic carbon, electrical conductivity, and pH) remaining constant, similar to Li et al. (2014). Correlation analysis further elucidated that soil organic carbon, total nitrogen, and pH were the most important factors determining soil macro-faunal distribution.

However, no significant differences in total density or diversity indices were observed between afforested sites (Shrub and Tree) and cultivated sites (Farm). This contrasted with our first hypothesis that cropland conversion to agroforestry would facilitate greater soil macro-faunal diversity, and with Liu et al. (2015a), who found greater contributions of manually afforested shrubland to ground-dwelling arthropod diversity compared to naturally restored grassland. This suggests limited ecological effectiveness of afforested plantations on soil macro-faunal density and diversity relative to natural restoration of abandoned croplands, contradicting our second hypothesis.

Numerous empirical studies have demonstrated the high economic and labor costs of artificial afforestation for restoring abandoned croplands in desertified regions (Sun et al., 2004; Zhao et al., 2009). Our results imply that natural restoration of abandoned croplands under exclosure is an effective and optional strategy for soil biological diversity conservation, despite requiring long-term recovery in the arid and semi-arid agro-pasture zone of northern China (Zhao et al., 2009; Zida et al., 2011). Given the substantial predator taxon richness observed at the Shrub site, shrubs may be preferable to trees for afforestation in abandoned croplands. Shrub cover creates an "arthropod island" that facilitates soil arthropods beneath the canopy (Zhao and Liu, 2013). Canepuccia et al. (2009) and Doblas-Miranda et al. (2009) elucidated the importance of plant (biotic) and soil (abiotic) interplay as key factors determining soil active arthropod community distribution in shrubland.

5 Conclusions

This study provides insights into the consequences of land management practices on soil macro-faunal communities and soil physical-chemical characteristics. We found that conversion of cropland to afforested plantation and naturally restored grassland caused major changes in arthropod activity, taxonomic composition, and trophic structure. Naturally restored grassland facilitated taxon density and richness of functional groups in the soil macro-faunal community and proved an effective strategy for biological diversity conservation relative to artificial afforestation in abandoned croplands. However, artificial afforestation had limited ecological effect on soil macro-faunal community structure, although shrubland practices were somewhat beneficial for improving arthropod predator diversity and related trophic structure. Specifically, shrubs may be preferable to trees for afforestation in abandoned croplands for desertification control and recovery of desertified grassland ecosystems in the arid and semi-arid agro-pasture transition zone of northern China.

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Note: Figure translations are in progress. See original paper for figures.