How long should the fully hillside-closed forest protection be implemented on the Loess Plateau, Shaanxi, China?

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ABSTRACT

Background. Restoration of degraded forest ecosystem is crucial for regional sustainable development. To protect the country's fragile and fragmented environment, the Chinese government initiated an ecological engineering project, the Natural Forest Protection Program, in seventeen provinces in China beginning in 1998. Fully hillside-closed forest protection (vegetation restoration naturally without any artificial disturbance) was one of vital measures of the Natural Forest Protection Program applied nation wide. Whether plant diversity, biomass and age structure of dominant tree species and soil nutrients in protected stands may become better with increase of protected period are still open problems.

Methods. We investigated community diversity, biomass of dominant tree species, age structures, and analyzed soil chemical properties of a *Pinus tabulaeformis* population at protected sites representing different protected ages at Huanglongshan Forest Bureau on the Loess Plateau, Shaanxi, China.

Results. Plant species richness of *Pinus tabulaeformis* community was significantly affected ($p < 0.05$) by forest protection and the effect attenuated with protection age. Shannon evenness index of plant species generally increased with protection age. Stands protected for 45 years had the highest tree biomass and considerable natural regeneration capacity. Contents of organic carbon, available phosphorus and available potassium in top soil increased in protected stands less than 45 years, however decreased significantly thereafter. Long-term forest protection also decreased the content of mineral nitrogen in top soil.

Discussion. We found that the richness of shrubs and herbs was significantly affected by forest protection, and evenness indices of tree, shrub and herb increased inconsistently with protected ages. Forest protection created more complex age structures and tree densities with increasing age of protection. Content of soil mineral nitrogen at 0–20 cm soil depth showed a decreasing trend in stands of up to 30 years. Soil available phosphorus and potassium contents were higher in stands with greater proportions of big and medium trees. Long-term protection (>45 years) of *Pinus tabulaeformis* stands in southeast Loess Plateau, China, may be associated with decreasing plant species richness, proportion of medium to large trees, dominant biomass of *Pinus tabulaeformis* and soil nutrients.

Subjects Biodiversity, Conservation Biology, Ecology, Plant Science, Soil Science
Keywords *Pinus tabulaeformis*, Optimal protection age, Restoration, The Loess Plateau, Fully hillside-closed forest protection

INTRODUCTION

Ecological restoration is being recognized as an international priority (*Aronson & Alexander, 2013*; *Wortley, Hero & Howes, 2013*) and it plays a crucial role in rebuilding ecological equilibrium and reversing ecosystem degradation (*Ma, Lv & Li, 2013*). As a part of ecological engineering (*Mitsch, 2012*), the practice is being widely incorporated into natural resource strategies from the local to global level (*Wortley, Hero & Howes, 2013*).

To protect the country's fragile and fragmented environment, the Chinese government initiated an ecological engineering project, the Natural Forest Protection Program (NFPP), beginning in 1998 (*Xu et al., 2006*). Logging and harvesting of partial or full timber was prohibited in protected areas from 1998 to 2008 (*Xu et al., 2006*). Fully hillside-closed forest protection (vegetation restoration naturally without any artificial disturbance) was applied nation-wide. Ecosystems have the capacity to self-organize and the self-design or self-organizational properties of natural systems is an essential component to ecological engineering (*Bergen, Bolton & Fridley, 2001*). Obviously, fully hillside-closed forest protection is in accord with the ecological engineering principle self-design.

The previous studies regarding NFPP have mainly focused upon the introduction of the related policy issues, the spatial-temporal succession of regional vegetation (*Huang et al., 2014*) and ecological restoration programs and payments (*Yin & Zhao, 2012*). However, a range of questions remain, particularly in relation to stand function and associated environmental parameters following stand protection. We hypothesize that fully hillside-closed forest protection may promote plant diversity, biomass and age structure of dominant tree species and soil nutrients with increase of protected period. The objectives of this study are to address a few of these key knowledge gaps, including: (i) do the stands exhibit significant differences in plant assemblage; (ii) does soil fertility change with stand age structure; (iii) can a functional relationship be defined regarding length of stand protection and stand quality, i.e., are stands protected for longer time frames ''better'' than other stands; and (iv) based on findings of i–iii above, can a preliminary estimate regarding the optimal time span for *Pinus tabulaeformis* stands be recommended to the Natural Forest Protection Program?

MATERIALS AND METHODS

Site description

The study was conducted in Huanglong County ($35°28'49''$–$36°02'01''$N, $109°38'49''$–$110°12'47''$E) on the southeast Loess Plateau, Shaanxi, China. Stands in this area (a part of NFPP area) play key ecological roles in abatement of soil erosion and mitigation of sand storm (*Chen et al., 2014*). The vegetation type is a northern deciduous broad-leaved forest sub-region. *Pinus tabulaeformis* is dominant tree species in the currently existing stands. The associated tree species are *Quercus liaotungensis*, *Syringa oblate*, *Populus davidiana*, *Prunus davidiana*, *Betula platyphylla* and *Toxicodendron vernicifluum.* Shrubs and herb species in the understory are abundant. The altitude ranges from 1,100 to 1,300 m. It is dominated by a warm temperate and semi-humid continental climate. The annual average precipitation is 612 mm and the mean atmospheric temperature is 8.6 °C. Cinnamon soil

is the main soil type in the forest region. Due to poor communication and a small human population in the past years, stands on some special sites have not been disturbed since 1950, especially since 1998. We consulted forest resource archive data of Huanglongshan Forest Bureau, Yanan, Shaanxi, China to find the year of forest protection and chose plots from forest farms (Fig. 1). According to the data, stands with protected age sequences were found in four forest farms (Table 1).

Field methods

We chose plots randomly. To find typical stand plots in the same protected age, not only similar altitude and canopy density, but also various directions, gradients, positions and density of dominant tree species were considered as principles. The field investigation and sampling was conducted between June 5 and July 15, 2003. Each plot of trees, shrubs and herbs was 20 m × 20 m, 2 m × 2 m and 1 m × 1 m respectively. Five sub-plots of shrubs, herbs and regenerating seedlings were arrayed diagonally in each tree plot respectively (Fig. 2). The indices, species, number, Height (H), diameter at breast height (DBH) and canopy density of trees, and species, height, cover ratio, number of shrubs, herbs and regenerating seedlings were measured. All community data were collected from 27 tree plots spreading among the age cohorts and 270 sub-plots (Table 1). Three soil samples were obtained randomly by a special drill in each tree plot. Surface soils (0–20 cm depth) at all sites were assessed for soil properties including organic carbon, mineral nitrogen, available phosphorous and potassium.

Community diversity

The diversity–productivity relationship (DPR) has been paid much attention during the past two decades (*Hooper et al., 2005*). In most DPR studies, richness has been chosen as the index of species diversity to define and interpret DPRs (*Zhang, Chen & Reich, 2012*). However, the simplex index cannot completely represent species diversity (*Bock, Jones & Bock, 2007*) in relation to ecosystem functioning for it ignores the effect of species evenness on interspecific interactions (*Hillebrand, Bennett & Cadotte, 2008*; *Kirwan et al., 2007*; *Turnbull & Hector, 2010*). Based on 54 studies, the importance of species richness and evenness in influencing diversity-associated productivity has been demonstrated in a meta-analysis (*Zhang, Chen & Reich, 2012*). In this study, we chose indices of richness and evenness to reflect characteristics of community. Species richness index (S) was derived from field survey data. To characterize the diversity of the stand community, the Shannon–Wiener index (H') and evenness index (J') were calculated as the following:

Shannon–Wiener index $H' = -\sum P_i \ln P_i$

Shannon evenness index $J' = \dfrac{H'}{\ln S}$

where P_i is the relative frequency of the ith species, and S is total number of species in plots and subplots (*Magurran, 2004*).

Biomass of dominant tree species

Average DBH (cm) and height (m) of *Pinus tabulaeformis* in each plot were calculated and living biomass (Mgha^{-1}) of whole trees (*Pinus tabulaeformis*) were estimated according to
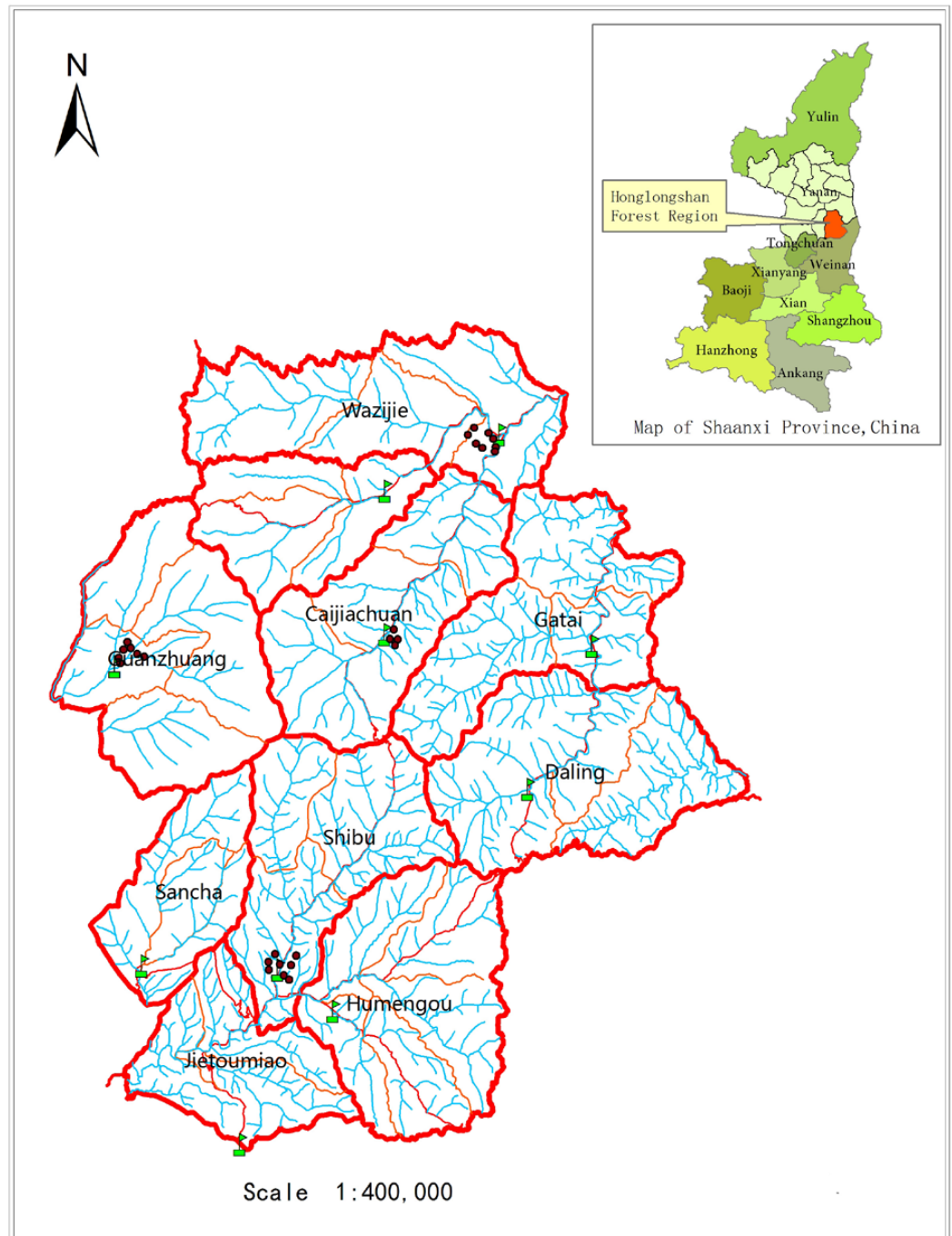
Figure 1 Position of plots. Dots on the figure were plots chosen in each forest farm (Map credit: Huang-longshan Forest Bureau, Yanan, Shaanxi, China).

Table 1 General information of plots.

Forest farm	Plot no.	Altitude (m)	Direction	Gradient (°)	Position	Density of dominant tree species (trees ha⁻¹)	Canopy density	Protecting age (a)
	1	1,170	Southeast	27	Upper	1,025	0.30	
	2	1,150	Southeast	29	Middle	1,075	0.35	
Shibu	3	1,165	Northeast	24	Middle	1,075	0.30	16
	4	1,135	Northeast	26	Lower	1,100	0.30	
	5	1,295	North	19	Middle	1,050	0.30	
	6	1,154	North	22.3	Middle	1,050	0.60	
	7	1,167	Northwest	24	Lower	675	0.50	
Guanzhuang	8	1,180	South	35	Upper	700	0.70	30
	9	1,165	South	35	Lower	1,350	0.60	
	10	1,180	South	22	Upper	1,375	0.60	
	11	1,163	South	25	Upper	1,050	0.50	
	12	1,170	North	24	Upper	750	0.60	
	13	1,160	North	22.3	Middle	800	0.70	
	14	1,175	North	21	Upper	625	0.60	
Wazijie	15	1,163	North	23	Middle	650	0.70	45
	16	1,154	North	26	Lower	600	0.70	
	17	1,120			Gully bottom	730	0.70	
	18	1,130	North	10	Lower	760	0.60	
	19	1,150	North	8	Ridge top	640	0.70	
	20	1,200	Northeast	19	Middle	1525	0.60	
	21	1,155	Northern	5	Ridge top	1,550	0.40	60
	22	1,150	North	18	Upper	1,725	0.40	
	23	1,130	North	16	Lower	1,475	0.40	
Caijiachuan	24	1,205	Northeast	10	Middle	1,900	0.30	
	25	1,200	Northeast	5	Lower	1,700	0.30	75
	26	1,185			Mesa	1,425	0.30	
	27	1,135	North	18	Middle	1,400	0.40	

the literature (*Chen & Peng, 1996*; *Pan et al., 2004*).

$$Y = 15.525 + 0.6269v$$

$$\ln v = 0.99138 \ln \left(D^2 H \right) - 10.30211$$

where Y is the living biomass of trees (Mgha⁻¹), v is the stand growing stock (m³ ha⁻¹), D (cm) is diameter at breast height and H (m) is height.

Combining the density of dominant tree species (Table 1) with equations, the biomass of *Pinus tabulaeformis* in protected stands was determined.

Age structures

DBH of tree species is correlated significantly to their ages under the same environmental condition (*Parker & Peet, 1984*). Lacking analytic wood data, we adopted DBH structures of *Pinus tabulaeformis* population instead of its age structures. Combining DBH and H,
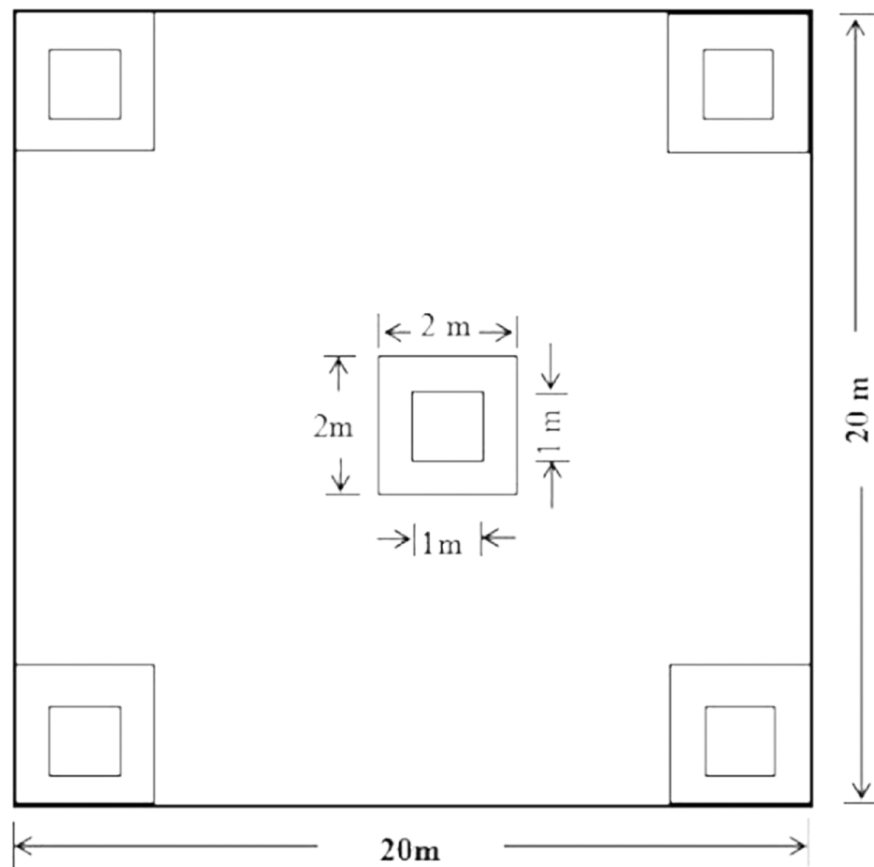
Figure 2 **Layout of subplots.** The plots 20 m × 20 m, the subplots 2 m × 2 m and 1 m × 1 m were used for the investigation of trees, shrubs and herbs respectively.

age structures of *Pinus tabulaeformis* population were classified as following: I seedling, $H \leq 0.30$ m; II young tree, 0.30 m $< H \leq 2.00$ m, DBH ≤ 6.00 cm; III small tree, $H > 2.0$ m, 6.0 cm $<$ DBH ≤ 12.0 cm; IV medium tree, 12.0 cm $<$ DBH ≤ 20.0 cm; V big tree, DBH > 20.0 cm. The ratio of seedlings, young trees, small trees, medium trees and big trees in stands with the same protection age was used to illustrate age structures. The probable age of an individual was determined by their whorled branches.

Chemical analyses

Analyses were made on air-dry soil material that passed through a 2 mm sieve. Soil organic carbon content (SOC) was determined by dry combustion with a TOC/TON analyzer (TOC-VTH-2000A; Shimadzu Corporation, Japan). Soil mineral nitrogen (ammonium nitrogen, NH^+_4-N and nitric nitrogen, NO_3^--N) content was determined by the colorimetric method with automatic flow injection (AA3, BRAN + LUEBBE; Germany). Available phosphorus content was extracted in 0.5M $NaHCO_3$ and determined by Mo-Sb colorimetry. Available potassium content was determined by method of flame photometry (*Bao, 2000*).

Table 2   Richness of plant species in protected stands.

Resoration age(a)	Tree	Shrub	Herb
16	Pinus tabulaeformis Populus davidiana Syringa oblata	Lespedeza dahurica Lespedeza floribunda Rosa hugonis Sophora viciifolia	Astragalus kifonsanicus Artemisia mongolica Artemisia giraldii Aster tataricus Bothriochloa ischaemum Bupleurum chinense Kengia serotina Lamium barbatum Patrinia heterophylla Rhaponticum uniflorum Scutellaria baicalensis Viola chaerophylloides
30	Betula platyphylla Conus walteri wanger Pinus tabulaeformis Prunus davidiana Prunus tomenosa Xanthoceras sorbifolia Quercus Liaotungensis Syringa oblata	Acer ginnala Berberis dielsiana Clematis brevicaudata Clematis fruticosa Cotoneaster multiflorus Lespedeza dahurica Lonicera ferdinandii Ostryopsis davidiana Periploca sepium Rhamnus davurica Rhamnus utilis Rosa hugonis Rubus corchorifolius Sophora viciifolia Spiraea fritschiana Ziziphus jujube var.spinosus	Adenophora potaninii Adenophora stricta Agrimonia pilosa Anaphalis margaritacea Artemisia giraldii Artemisia gmelinii Artemisia mongolica Aster tataricus Bothriochloa ischaemum Bupleurum chinense Carpesium divaricatum Discorea nippnica Gentiana macrophylla Kengia serotina Leontopodium leontopodioides Lilium pumilum Lysimachia barystachys Melissitus ruthenicus Patrinia heterophylla Pennisetum clandestinum Polygonatum odoratum Potentilla supina Sanguisorba officinalis Saussurea morifolia Saussurea nivea Saussurea petrovii Saussurea salsa Scutellaria baicalensis Spodiopogon sibiricus

Table 2 (*continued*)

Resoration age(a)	Tree	Shrub	Herb
			Thalictrum prezewalskii
			Urena lobata
			Vicia unijuga
			Viola chaerophylloides
			Viola selkirkii
			Viola yedoensis
45	*Betula platyphylla*	*Acer ginnala*	*Agrimonia pilosa*
	Pinus tabulaeformis	*Lespedeza dahurica*	*Anaphalis margaritacea*
	Quercus Liaotungensis	*Lonicera maccki*	*Artemisia mongolica*
	Syringa oblata	*Rubus corchorifolius*	*Aster tataricus*
		Spiraea fritschiana	*Bothriochloa ischaemum*
			Kengia serotina
			Neottianthe cucullata
			Potentilla discolor
			Spodiopogon sibiricus
			Urena lobata
			Viola chaerophylloides
			Viola japonica var. stenopetala
			Viola selkirkii
			Viola yedoensis
60	*Pinus tabulaeformis*	*Acer ginnala*	*Adenophora stricta*
	Populus davidiana	*Berberis dolichobotrys*	*Anaphalis margaritacea*
	Prunus tomenosa	*Cotoneaster zbakelii*	*Artemisia gmelinii*
	Quercus Liaotungensis	*Lespedeza dahurica*	*Artemisia mongolica*
	Syringa oblata	*Ostryopsis davidiana*	*Aster tataricus*
	Toxicodendron vernicifluum	*Rosa hugonis*	*Bothriochloa ischaemum*
		Rubus corchorifolius	*Bupleurum chinense*
		Spiraea fritschiana	*Kengia serotina*
			Neottianthe cucullata
			Polygonatum sibircum
			Potentilla discolor
			Scutellaria baicalensis
			Spodiopogon sibiricus
			Vicia cracca
			Viola chaerophylloides
			Viola selkirkii
			Urena lobata

Table 2 (continued)

Resoration age(a)	Tree	Shrub	Herb
75	Pinus tabulaeformis	Acer ginnala	Anaphalis margaritacea
	Populus davidiana	Clematis fruticosa	Artemisia mongolica
	Quercus Liaotungensis	Cotoneaster zbakelii	Aster tataricus
	Syringa oblata	Indigofera amblyantha	Bothriochloa ischaemum
	Toxicodendron vernicifluum	Lespedeza dahurica	Kengia serotina
		Lonicera maccki	Sanguisorba officinalis
		Ostryopsis davidiana	Spodiopogon sibiricus
		Rubus corchorifolius	Thalictrum prezewalskii
		Spiraea fritschiana	Urena lobata
			Viola chaerophylloides
			Vicia unijuga
			Viola selkirkii

Data processing and analysis

SPSS 17.0 and Origin8.0 (OriginLab Corporation) software were used for statistical analysis and plotting. Histograms were performed by SPSS 17.0 based on the residual distribution. We hypothesized the variance was homogeneous firstly. Then, homogeneity test of variance was performed by SPSS 17.0. If our hypothesis was true, one-way analysis of variance (ANOVA) following Fisher's least significant difference (LSD) test ($p < 0.05$) was used to compare the protection age effects on diversity of plant community and soil nutrients respectively.

RESULTS

Diversity of plants in protected stands

Data from 27 plots (Table 1) representing protection age of stands and richness of trees, shrubs and herbs (Table 2) were compared. Richness index of trees (8), shrubs (17) and herbs (35) was highest in the stand protected for 30 years (Table 2). A significant difference in the tree species richness index was observed in the 30 year protected stand compared to stands protected for 16 years ($n = 11$, $p = 0.000$) and 45 years ($n = 14$, $p = 0.000$), but not in other stands with different protected ages (Fig. 3).The richness index of within stand shrubs differed significantly between stands protected for 30 years compared to stands protected for 16 years ($n = 55$, $p = 0.000$), 45 years ($n = 65$, $p = 0.000$), 60 years ($n = 50$, $p = 0.000$) and 75 years ($n = 50$, $p = 0.000$) (Fig. 3). Significant differences in the within-stand herb richness index were also found in stands protected (i) 16 years and 60, 75 years, (ii) 45 years and 60 years, 75 years (Fig. 3). The within stand herb richness index in the stands protected for 30 years differed significantly from stands protected for 16 years ($n = 55$, $p = 0.000$), 45 years ($n = 65$, $p = 0.000$), 60 years ($n = 50$, $p = 0.000$) and 75 years ($n = 50$, $p = 0.000$) (Fig. 3). Richness of within stand herb at stands protected for 16 years also varied significantly from stands protected for 60 years and 75 years (Fig. 3).

Shannon-Wiener evenness index of tree, shrub and herb was highest in stands protected for 30 years, 45 years and 75 years respectively (Fig. 4A). The index of herb generally increased with protected ages except in stands protected for 16 years to 30 years (Fig. 4A).
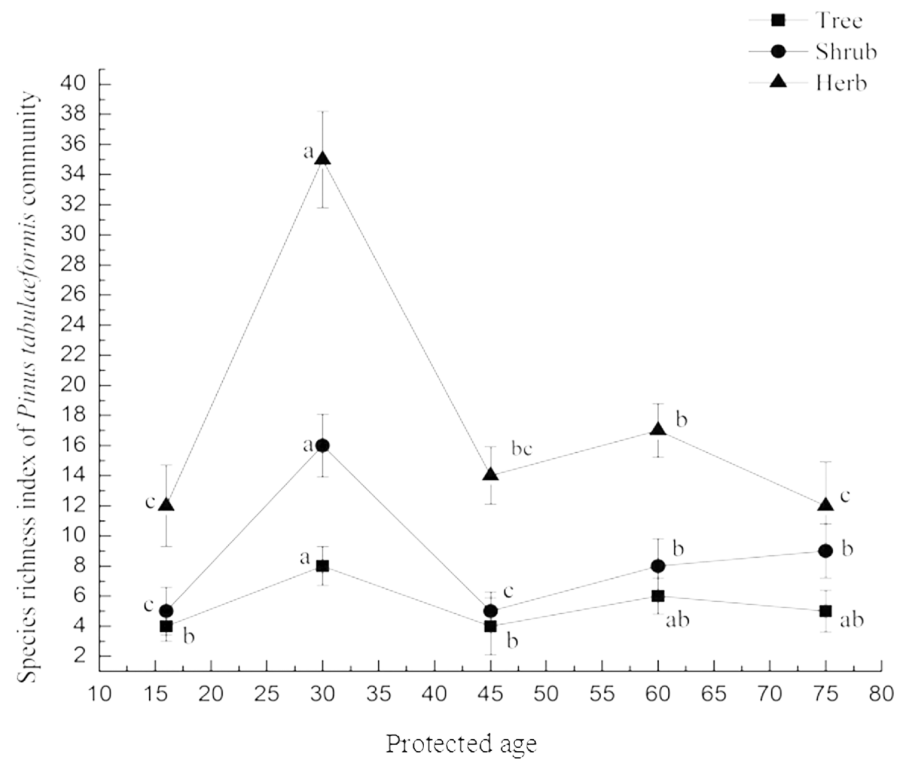
Figure 3 **Richness of *Pinus tabulaeformis* community in protected stands.** The values are the mean ± SD. Different letters in the same layer in the figure indicate significant differences between groups based on LSD ($p < 0.05$). Confidence interval of 95% for richness of tress, shrubs and herbs among protection years is [3.32,7.48], [2.03,14.37] and [5.93,30.07] respectively.

However, the index of tree and shrub fluctuated with stand protected years and did not follow a trending relationship (Fig. 4A). Tree and shrub Shannon-Wiener index increased with stand protection age, with the exception of tree index 30–45 year stand protection and shrub index 45–60 year stand protection (Fig. 4A). To clearly show the trend of evenness index with age, linear fit of trees, shrubs and herbs was given out by Origin8.0 (OriginLab Corporation). With protection year increase, species distribution tended to be more homogeneous (Fig. 4B).

Biomass of *Pinus tabulaeformis* in protected stands

Biomass of *Pinus tabulaeformis* increased in stands until 45 years of forest protection; however, for sites older than this protection age, stand biomass decreased (Fig. 5). Peak biomass was 70.60 ± 8.00 t ha^{-1} in the stand protected for 45 years, while biomass in the stand protected for 75 years (19.90 ± 9.20 t ha^{-1}) was lower than the stand protected for 16 years (23.70 ± 17.10 t ha^{-1}) (Fig. 5).

Age structure of *Pinus tabulaeformis* population in protected stands

Although age classes of *Pinus tabulaeformis* occurred in protected stands, they varied greatly (Fig. 6). Only young (II) and small trees (III) were found in the stand protected for 16 years, small (III) and medium trees (IV) dominated the stand protected for 30 years (Fig. 6). For
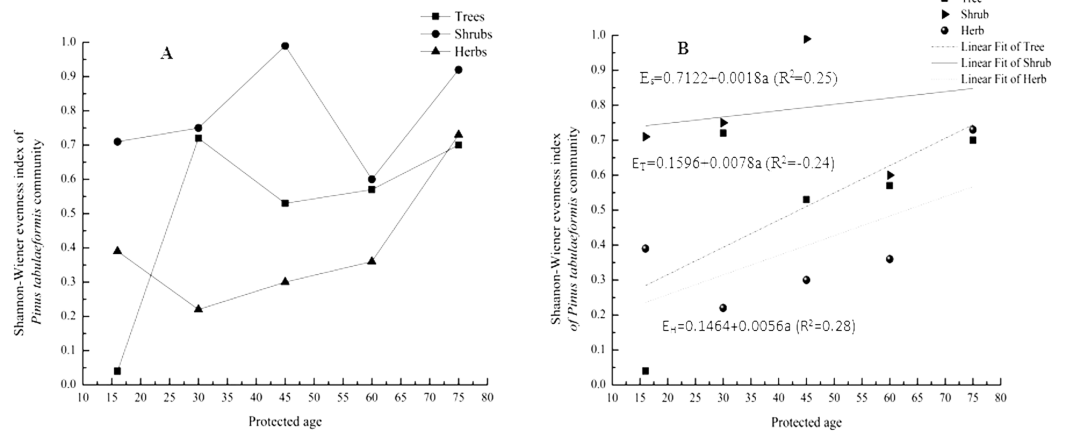
Figure 4 **Shannon–Wiener evenness index of *Pinus tabulaeformis* community in protected stands.**
Letters ET, ES, EH and a in Fig. 4B stand for the evenness index of tree, shrub, herb and protection year respectively. Confidence interval of 95% for evenness of tress, shrubs and herbs is [0.16, 0.85], [0.60, 0.99] and [0.16, 0.64] respectively. Equations in Fig. 4B show the relationship between evenness index and protected year of stands. E_T, E_S, E_H show a represented evenness index of tree, shrub, herb and protected year of stands, respectively.
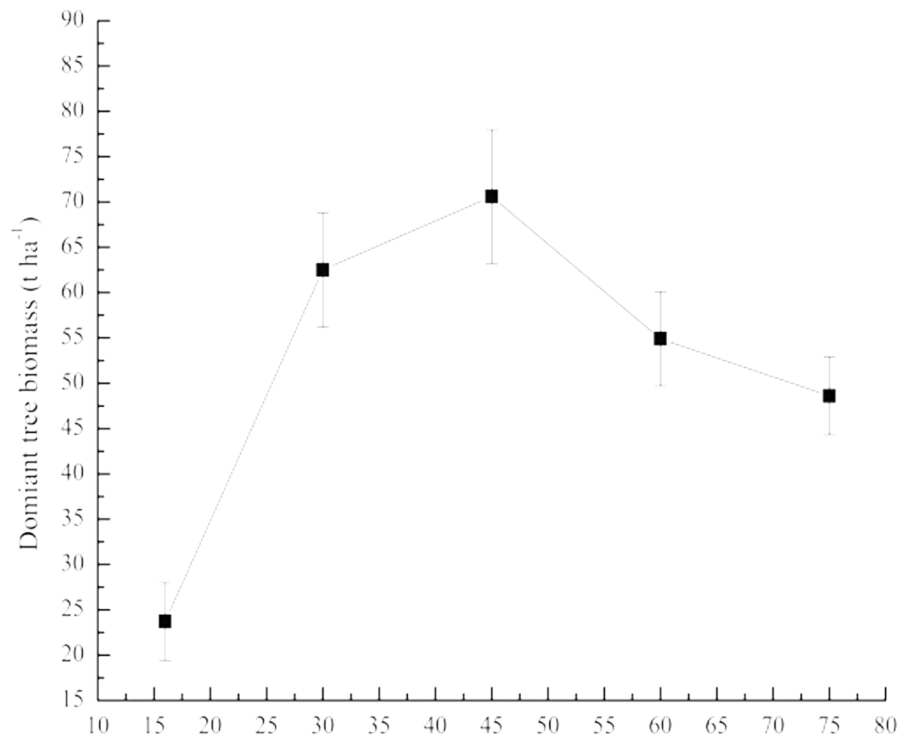
Figure 5 **Biomass of *Pinus tabulaeformis* in protected stands.** Error bars are from one-way analysis of variance (ANOVA). Confidence interval of 95% for biomass of dominant tress is [22.87, 74.25].
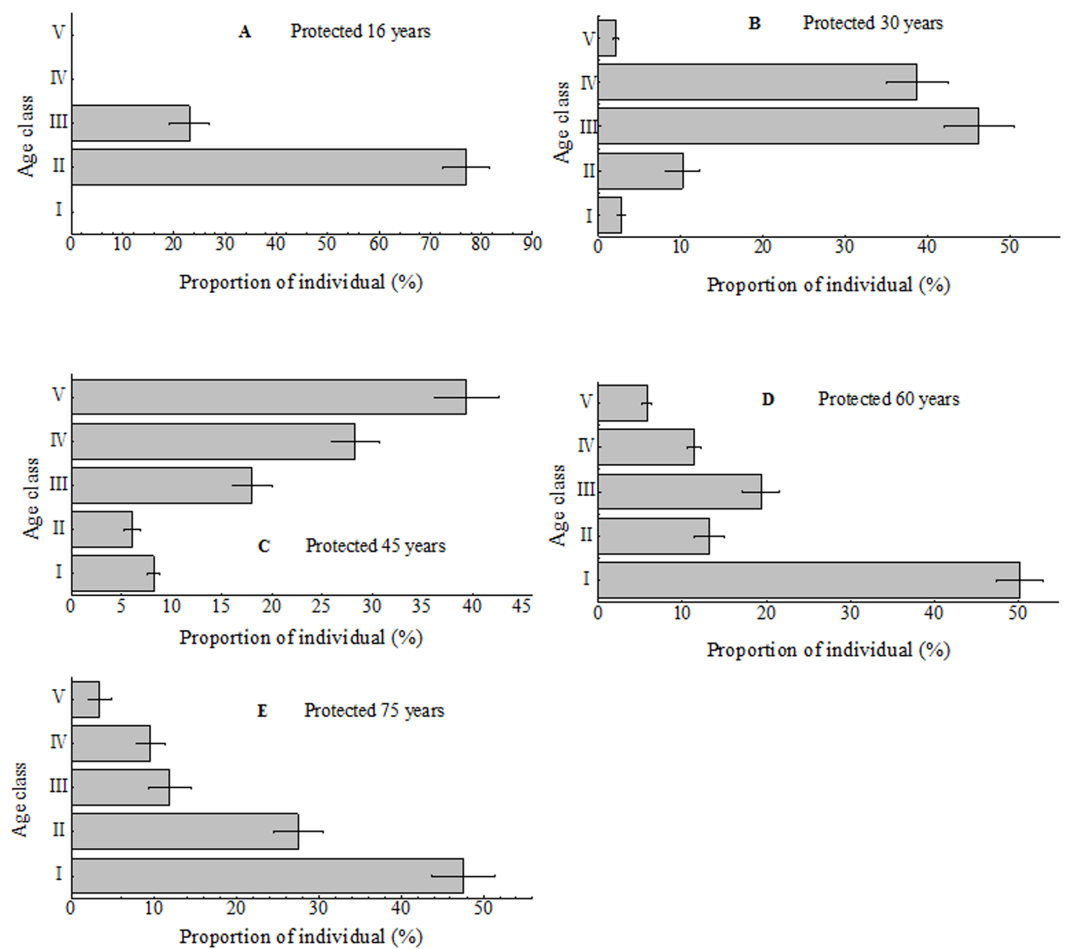
Figure 6 **Age structure of *Pinus tabulaeformis* population in protected stands.** The Roman numerals (I–V) in figures stand for age structures of *Pinus tabulaeformis* population. I seedling, $H \leq 0.30$ m; II young tree, 0.30 m 2.0 m, 6.0 cm < DBH $\leq$ 12.0 cm; IV medium tree, 12.0 cm < DBH $\leq$ 20.0 cm; V big tree, DBH > 20.0 cm.

the stand protected for 45 years, big (V) and medium trees (IV) were main components, but seedlings (I) and young trees were considerable also (Fig. 6). In contrast, for stands protected for 60 and 75 years, seedlings (I) were the dominant component, followed by young (II) and small trees (III), with big trees (V) lowest in distribution (Fig. 6).

Soil nutrients

Significant differences of soil organic carbon content at 0–20 cm soil depth were observed between the stands, with higher soil organic carbon content observed in stands protected for longer than 30 years (Fig. 7A). Content of mineral nitrogen at 0–20 cm soil depth demonstrated significant differences in stands before and after the protected 30 years (Fig. 7B). No significant differences were found between stands protected for 16 years and 30 years, and among stands after 30 years (Fig. 7B). Content of available phosphorus at 0–20 cm soil depth increased as protection of stand age increased, with significant differences observed mostly at youngest and oldest stand ages (Fig. 7C). No significant
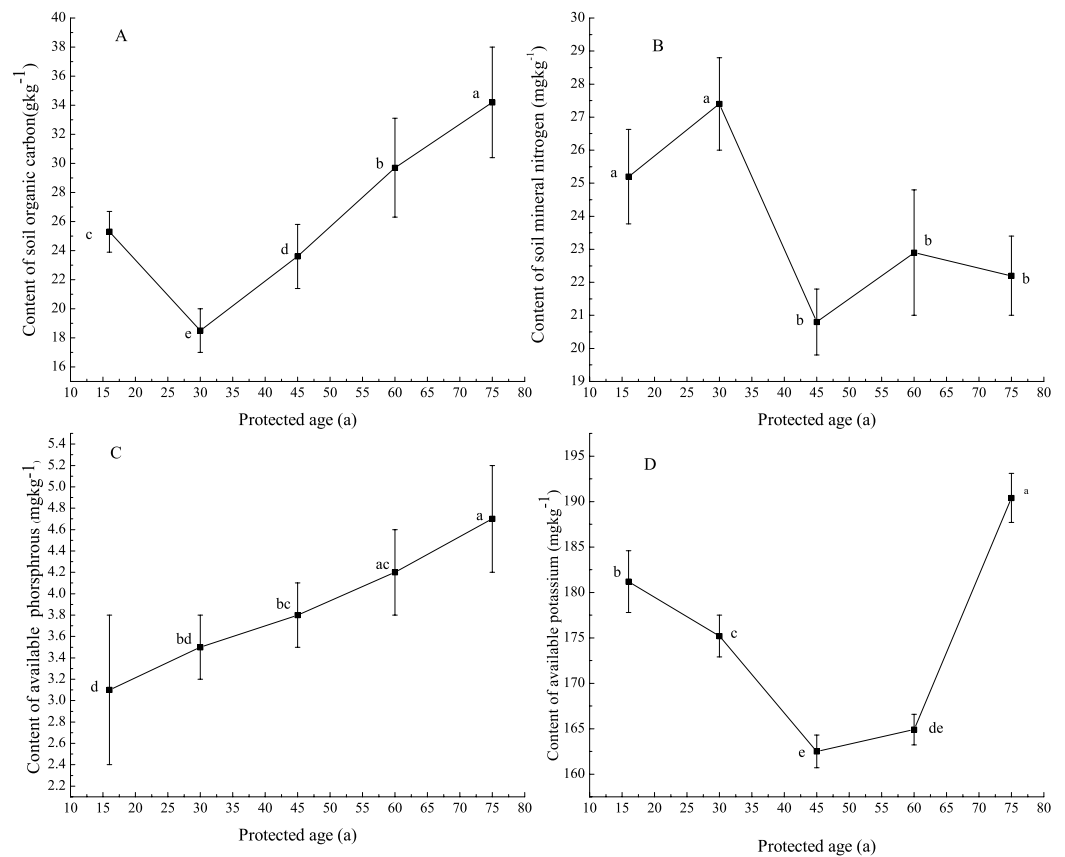
Figure 7 Soil nutrients in protected stands. The subfigures (A), (B), (C) and (D) demonstrate the dynamics of soil organic carbon (gkg^{-1}), soil mineral nitrogen (mgkg^{-1}), soil available phosphorus (mgkg^{-1}) and soil available potassium (mgkg^{-1}) with protection of stands, respectively. Disparate lowercase letters on the figure represent significant difference ($p < 0.05$).

difference in available phosphorus was observed in stands between 30 and 45 years of protection, and between 45 and 60 years of protection (Fig. 7C). Content of available potassium at 0–20 cm soil depth decreased in stands younger than 45 years and thereafter increased (Fig. 7D). Significant differences were demonstrated among stands with different protection ages, except at ages 45 and 60 (Fig. 7D).

DISCUSSION

Response of plant diversity to forest protection

Species richness is one measure of biodiversity and is very important for ecosystem functioning, stability and integrity (*Coroi et al., 2004*). We found that richness of shrubs and herbs was significantly affected by forest protection, although richness (Fig. 3) and evenness (Fig. 4) indices of tree, shrub and herb increased in an unpredictable manner with protected age. The richness of plant species increased in stands protected for 16 years (species numbers of tree, shrub and herb are 3, 4 and 12 respectively) to 30 years (species numbers of tree, shrub and herb are 8, 16 and 35 respectively), decreased in stands protected for 30 years to 45 years (species numbers of tree, shrub and herb are 4, 5 and

14 respectively) and remained fairly stable in stands protected for longer than 45 years (species numbers of tree, shrub and herb are 6, 8 and 17 respectively in stands protected for 60 years; species numbers of tree, shrub and herb are 5, 9 and 12 respectively in stands protected for 75 years) (Table 2). Due to adequate sunlight and growing spaces, some pioneer tree species (*Populus davidiana*, *Betula platyphylla*) and drought resistant shrubs (*Rubus corchorifolius*, *Rosa hugonis*, etc.) and herbs (*Artemisia gmelinii*, *Saussurea petrovii*, etc.) were more prevalent in the younger forest protection sites, increasing plant species richness of these stands (Table 2). With the growth of trees, canopy density increased and some drought resistant plant species disappeared. Advance regeneration seedlings in stands protected for 45 years and older made up a large proportion of the species observed, impeding invasive plant species and stabilizing plant diversity of the community assemblage. Inherent spatial variability within the landscape may provide a possible explanation for this pattern observed, since *Pinus tabulaeformis* stands are distributed across variable site conditions within the region. Soil moisture is considered to be the key limiting factor on the Loess Plateau for differences in plant species growth and regeneration (*Chen et al., 2014*) and it is possible that the differences in soil property as observed in this study affected plant-available moisture.

Forest protection in Huanglongshan forest region, Yanan, Shaanxi, China was initiated in 1950 from forest resources archives. Stand structure within the protection area under the natural restoration condition differed. Stands with diversified age structure were richer in species than stands with less diversified structure (*Thompson, 2012*). Findings in this study partly support this notion. Stands protected for greater than 16 years had more species with diverse age structures and plant species richness (Fig. 3). Age class structure in stands protected for 30 years were generally simpler than stands protected for longer periods (Fig. 6). However, stands older than 30 years of protection had lower richness index of tress and understory species (Fig. 4).

Our results suggest that sustainable forest protection can potentially contribute to plant diversity conservation by increasing species richness generally (Table 2) and promoting even distribution of trees and herbs (Fig. 4).

Response of age structure to forest protection

Forest protection created more complex age structures (Fig. 5) and tree densities with increasing age of protection (Table 1). Seedlings, medium and big trees were absent in younger stands (Fig. 6) which indicated tree biomass was low (Fig. 5) and lacked natural regeneration capacity. Although plants species were most abundant in stands protected for 30 years (Fig. 3), this protection age contained the lowest proportion of big trees (V) among age classes (Fig. 6) limiting tree biomass. Both seedlings (Fig. 6) and density of trees (Fig. 3) in older (>60 years) protected stands were higher than in younger stands, suggesting a better natural regeneration capacity. However, more seedlings and small trees without adequate big trees (Fig. 6) in some older stands were evidence of insufficient productivity of such stands (Fig. 5).

Our results support the widely accepted view that the rate of stand biomass accumulation peaks in the early stage of development, usually at the time of canopy closure, and declines

thereafter (*Acker et al., 2002*; *McMahon & Schlesinger, 2010*; *Sarah Lesley Taylor, 2005*; *Xu et al., 2012*). The stand protected for 45 years had not only the highest canopy density (Table 1), but also the highest proportion of big trees and tree biomass as well as considerable seedling density (Fig. 6), suggesting adequate regeneration capacity at this age.

Response of soil nutrients to forest protection

Vegetation plays a key role in maintaining the soils in which they grow (*Mishra, Sharma & Khan, 2003*), by directly influencing soil nutrients accumulation and consequently soil development via above ground inputs (*Blazejewski et al., 2009*; *Drouin et al., 2011*; *Giese et al., 2000*). Litter fall and its decomposition is an important mechanism governing soil chemical properties (*Mishra, Sharma & Khan, 2003*), especially the upper soil layer (*Ma et al., 2007*).

In the present study, *Pinus tabulaeformis* tree growth (Fig. 5) and understory plant species richness increased quickly for stands protected less than 30 years (Fig. 3), however litter input to soil was lower due to the absence of big trees in these stands (Fig. 6). Tree and canopy density (Table 1) decreased in stands protected for more than 30 years, with highest values observed in stands protected for 45 years (Fig. 5). Increased litter input, decomposition rate and higher soil organic carbon contents were also observed at older forest sites (Fig. 7A).

Content of soil mineral nitrogen at 0–20 cm soil depth showed a decreasing trend in stands of up to 30 years of protection although no significant differences were found among stands (Fig. 7B). This trend does not support previous studies which have observed that young or developing stands accumulate forest floor nitrogen, tending towards relatively stable conditions in undisturbed mature forests.

The primary source of phosphorus and potassium in terrestrial ecosystems are derived from mineral materials in weathering parent rock (*Filippelli, 2008*; *Sheng, 2005*; *Smeck, 1985*; *Tiessen, Stewart & Cole, 1984*). A proportion of the released phosphorus and potassium, available in exchangeable and soluble (available) fractions, can be assimilated by plants and soil microorganisms directly (*Schachtman, Reid & Ayling, 1998*; *Sheng, 2005*). Soil phosphorus availability is also enhanced through phosphorus solubilizing and mineralizing microbial biomass (*Richardson & Simpson, 2011*). Many soil microorganisms excrete organic acids to directly dissolve rock potassium to bring the potassium into solution (*Bennett, 1998*; *Friedrich et al., 1991*; *Groudev, 2010*; *Ullman et al., 1996*).

In the present study, soil available phosphorus (Fig. 7C) and potassium (Fig. 7D) contents were higher in stands with greater proportions of big and medium trees. We suggest that the stands with greater biomass accumulated more litter and humic mineral in the top soil, which provided a substantial energy source and favorable conditions for microbial activity (*Fontaine, Mariotti & Abbadie, 2003*). In younger stands, more nutrients may be taken up by the vegetation during intense tree growth phase than can be replaced within the soil from mineral weathering and litter decomposition (*Brais, Camiré & Paré, 1995*) which may explain why soil available potassium decreased in stands of up to 45 years of protection in this study (Fig. 7D).

The optimal age for the fully hillside-closed forest protection

No restoration project is undertaken in a social vacuum (*Knight et al., 2010*). The goods and services provided by forests are an important source of income for local people in the rural part of China (*Ma, Lv & Li, 2013*). Even when the intentions of ecological restoration are good and the restoration strategy suitable for the environmental conditions (*Ma, Lv & Li, 2013*), restoration action will not be sustainable if it does not take into account the profit potential of local people.

Our results showed that long-term protection (>45 years) of *Pinus tabulaeformis* stands in southeast Loess Plateau, China, may be associated with decreasing plant species richness (Table 2), proportion of medium to large trees (Fig. 6), dominant tree biomass (Fig. 5) and soil nutrients (Fig. 7). In addition, proportion of seedlings was more than 45% when stands were protected for 60 and 75 years (Fig. 5). Forest tending operations are required to weaken competition among seedlings for sunlight, nutrients, moisture and space at those periods. We suggest that it is possible, based on the findings above, to couple forest management policy without exacerbating the poverty of local people, through the promotion of measured forest indices as evidence-based support for forest protection and use. For this region, we suggest the optimum forest protection age of 45 years would encourage maximum plant diversity and productivity, while supporting the socio-economic conditions of the local population for sustainable land use.

CONCLUSIONS

The present study has reported differences of plant diversity, changes in forest age structure and soil nutrients of *Pinus tabulaeformis* stands restoration in chronosequence on the southeast Loess Plateau, China. The richness of plant species significantly differed with age of forest protection, attenuating towards more even distribution with increasing age of forest protection. Sustainable forest protection not only hindered increased biomass of dominant trees, organic carbon content, available phosphorus and potassium in top soil, but it also abated proportion medium and big trees after protection of 45 years. Meanwhile, proportion of seedlings and young trees increased to aggravate competition of environmental resources. Our findings have practical implications. By using measured forest indices as evidence-based support for balancing forest management policy, ecological restoration and local economy development including sustainable timber harvesting, we conclude that the preliminary optimal age for forest protection in this area should be not more than 45 years. Forest tending operations have to be implemented thereafter.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Lin Hou conceived and designed the experiments, performed the experiments, analyzed the data, wrote the paper, reviewed drafts of the paper.
- Sijia Hou analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables.

Data Availability

The following information was supplied regarding data availability:
The raw data has been supplied as Supplementary File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.3764#supplemental-information.

REFERENCES

Acker SA, Halpern CB, Harmon ME, Dyrness CT. 2002. Trends in bole biomass accumulation, net primary production and tree mortality in Pseudotsuga menziesii forests of contrasting age. *Tree Physiology* **22**:213–217 DOI 10.1093/treephys/22.2-3.213.

Aronson J, Alexander S. 2013. Ecosystem restoration is now a global priority: time to roll up our sleeves. *Restoration Ecology* **21**:293–296 DOI 10.1111/rec.12011.

Bao SD. 2000. *Soil and agricultural chemistry analysis.* Beijing: China Agriculture Press.

Bennett PC. 1998. Microbial destruction of feldspars. *Mineralogical Magazine* **62A**:149–150 DOI 10.1180/minmag.1998.62A.1.79.

Bergen SD, Bolton SM, Fridley LJ. 2001. Design principles for ecological engineering. *Ecological Engineering* **18**:201–210 DOI 10.1016/S0925-8574(01)00078-7.

Blazejewski GA, Stolt MH, Gold AJ, Gurwick N, Groffman PM. 2009. Spatial distribution of carbon in the subsurface of riparian zones. *Soil Science Society of America Journal* **73**:1733–1740 DOI 10.2136/sssaj2007.0386.

Bock CE, Jones ZF, Bock JH. 2007. Relationships between species richness, evenness, and abundance in a southwestern Savanna. *Ecology* **88**:1322–1327 DOI 10.1890/06-0654.

Brais S, Camiré C, Paré D. 1995. Impacts of whole-tree harvesting and winter windrowing on soil pH and base status of clayey sites of northwestern Quebec. *Canadian Journal of Forest Research* **25**:997–1007 DOI 10.1139/x95-108.

Chen Y, Cao Y, Chen Y, Cao Y. 2014. Response of tree regeneration and understory plant species diversity to stand density in mature *Pinus tabulaeformis* plantations in the hilly area of the Loess Plateau, China. *Ecological Engineering* **73**:238–245 DOI 10.1016/j.ecoleng.2014.09.055.

Chen C, Peng H. 1996. Standing crops and productivity of the major forest-types at the Huoditang forest region of the Qinling mountains. *Journal of Northwest Forestry College* **11**:92–102.

Coroi M, Skeffington MS, Giller P, Smith C, Gormally M, O'Donovan G. 2004. Vegetation diversity and stand structure in streamside forests in the south of Ireland. *Forest Ecology & Management* **202**:39–57 DOI 10.1016/j.foreco.2004.06.034.

Drouin A, Saint-Laurent D, Lavoie L, Ouellet C. 2011. High-precision elevation model to evaluate the spatial distribution of soil organic carbon in active floodplains. *Wetlands* **31**:1151–1164 DOI 10.1007/s13157-011-0226-z.

Filippelli GM. 2008. The global phosphorus cycle: past, present, and future. *Elements* **4**:89–95 DOI 10.2113/GSELEMENTS.4.2.89.

Fontaine S, Mariotti A, Abbadie L. 2003. The priming effect of organic matter: a question of microbial competition? *Soil Biology & Biochemistry* **35**:837–843 DOI 10.1016/S0038-0717(03)00123-8.

Friedrich S, Platonova NP, Karavaiko GI, Stichel E, Glombitza F. 1991. Chemical and microbiological solubilization of silicates. *Acta Biotechnologica* **11**:187–196 DOI 10.1002/abio.370110302.

Giese LA, Aust WM, Trettin CC, Kolka RK. 2000. Spatial and temporal patterns of carbon storage and species richness in three South Carolina coastal plain riparian forests. *Ecological Engineering* **15**:S157–S170 DOI 10.1016/S0925-8574(99)00081-6.

Groudev SN. 2010. Use of heterotrophic microorganisms in mineral biotechnology. *Engineering in Life Sciences* **7**:299–306 DOI 10.1002/abio.370070404.

Hillebrand H, Bennett DM, Cadotte MW. 2008. Consequences of dominance: a review of evenness effects on local and regional ecosystem processes. *Ecology* **89**:1510–1520 DOI 10.1890/07-1053.1.

Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, Setala H, Symstad AJ, Vandermeer J, Wardle DA. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs* **75**:3–35 DOI 10.1890/04-0922.

Huang XH, Yuan H, Yu FK, Li XY, Liang QB, Yao P, Shao HB. 2014. Spatial–temporal succession of the vegetation in Xishuangbanna, China during 1976–2010: a case study based on RS technology and implications for eco-restoration. *Ecological Engineering* **70**:255–262 DOI 10.1016/j.ecoleng.2014.05.022.

Kirwan L, Lüscher A, Sebastià MT, Finn JA, Collins RP, Porqueddu C, Helgadottir A, Baadshaug OH, Brophy C, Coran C, Dalmannsdóttir S, Delgado I, Elgersma A, Fothergill M, Frankow-Lindberg BE, Golinski P, Grieu P, Gustavsson AM, Höglind M, Huguenin-Elie O, Iliadis C, Jørgensen M, Kadziuliene Z, Karyotis T, Lunnan T, Malengier M, Maltoni S, Meyer V, Nyfeler D, Nykanen-Kurki P, Parente J, Smit HJ, Thumm U, Connolly J. 2007. Evenness drives consistent diversity effects in intensive grassland systems across 28 European sites. *Journal of Ecology* **95**:530–539 DOI 10.1111/j.1365-2745.2007.01225.x.

Knight AT, Cowling RM, Mark D, Campbell BM. 2010. Mapping human and social dimensions of conservation opportunity for the scheduling of conservation action on private land. *Conservation Biology* **24**:1348–1358 DOI 10.1111/j.1523-1739.2010.01494.x.

Ma X, Heal KV, Liu A, Jarvis PG. 2007. Nutrient cycling and distribution in different-aged plantations of Chinese fir in southern China. *Forest Ecology & Management* **243**:61–74 DOI 10.1016/j.foreco.2007.02.018.

Ma H, Lv Y, Li H. 2013. Complexity of ecological restoration in China. *Ecological Engineering* **52**:75–78 DOI 10.1016/j.ecoleng.2012.12.093.

Magurran AE. 2004. *Measuring biological diversity*. Oxford: Blackwell Publishing.

McMahon SM, Schlesinger WH. 2010. Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences of the United States of America* **107**:3611–3615 DOI 10.1073/pnas.0912376107.

Mishra A, Sharma SD, Khan GH. 2003. Improvement in physical and chemical properties of sodic soil by 3, 6 and 9 years old plantation of Eucalyptus tereticornis: biorejuvenation of sodic soil. *Forest Ecology & Management* **184**:115–124 DOI 10.1016/S0378-1127(03)00213-5.

Mitsch WJ. 2012. What is ecological engineering? *Ecological Engineering* **45**:5–12 DOI 10.1016/j.ecoleng.2012.04.013.

Pan Y, Luo T, Birdsey R, Hom J, Melillo J. 2004. New estimates of carbon storage and sequestration in China's forests: effects of Age–class and method on inventory-based carbon estimation. *Climatic Change* **67**:211–236 DOI 10.1007/s10584-004-2799-5.

Parker AJ, Peet RK. 1984. Size and age structure of conifers forests. *Ecology* **65**:1685–1689 DOI 10.2307/1939148.

Richardson AE, Simpson RJ. 2011. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiology* **156**:989–996 DOI 10.1104/pp.111.175448.

Sarah Lesley Taylor DAM. 2005. Rate and causes of decline of mature and overmature balsam fir and spruce stands in New Brunswick, Canada. *Canadian Journal of Forest Research* **35**:2479–2490 DOI 10.1139/x05-142.

Schachtman DP, Reid RJ, Ayling SM. 1998. Phosphorus uptake by plants: from soil to cell. *Plant Physiology* **116**:447–453 DOI 10.1104/pp.116.2.447.

Sheng XF. 2005. Growth promotion and increased potassium uptake of cotton and rape by a potassium releasing strain of Bacillus edaphicus. *Soil Biology & Biochemistry* **37**:1918–1922 DOI 10.1016/j.soilbio.2005.02.026.

Smeck NE. 1985. Phosphorus dynamics in soils and landscapes. *Geoderma* **36**:185–199 DOI 10.1016/0016-7061(85)90001-1.

Thompson I. 2012. Biodiversity, ecosystem thresholds, resilience and forest degradation. *Unasylva* **62**:25–30.

Tiessen H, Stewart JWB, Cole CV. 1984. Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Science Society of America Journal* **48**:853–858 DOI 10.2136/sssaj1984.03615995004800040031x.

Turnbull LA, Hector A. 2010. Applied ecology: how to get even with pests. *Nature* **466**:36–37 DOI 10.1038/466036a.

Ullman WJ, Kirchman DL, Welch SA, Vandevivere P. 1996. Laboratory evidence for microbially mediated silicate mineral dissolution in nature. *Chemical Geology* **132**:11–17 DOI 10.1016/S0009-2541(96)00036-8.

Wortley L, Hero J-M, Howes M. 2013. Evaluating ecological restoration success: a review of the literature. *Restoration Ecology* **21**:537–543 DOI 10.1111/rec.12028.

Xu CY, Turnbull MH, Tissue DT, Lewis JD, Carson R, Schuster WSF, Whitehead D, Walcroft AS, Li J, Griffin KL. 2012. Age-related decline of stand biomass accumulation is primarily due to mortality and not to reduction in NPP associated with individual tree physiology, tree growth or stand structure in a Quercus-dominated forest. *Journal of Ecology* **100**:428–440 DOI 10.1111/j.1365-2745.2011.01933.x.

Xu J, Yin R, Li Z, Liu C. 2006. China's ecological rehabilitation: unprecedented efforts, dramatic impacts, and requisite policies. *Ecological Economics* **57**:595–607 DOI 10.1016/j.ecolecon.2005.05.008.

Yin R, Zhao M. 2012. Ecological restoration programs and payments for ecosystem services as integrated biophysical and socioeconomic processes— China's experience as an example. *Ecological Economics* **73**:56–65 DOI 10.1016/j.ecolecon.2011.11.003.

Zhang Y, Chen HYH, Reich PB. 2012. Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *Journal of Ecology* **100**:742–749 DOI 10.1111/j.1365-2745.2011.01944.x.