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The effect of *Robinia pseudoacacia* afforestation on soil and vegetation properties in the Loess Plateau (China): A chronosequence approach

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ABSTRACT

Revegetation is one of the primary management approaches for solving the problems caused by severe soil erosion worldwide. *Robinia pseudoacacia* was considered a promising tree for afforestation in the highly eroded region of the Loess Plateau due to its fast growth and ability to fix atmospheric nitrogen. However, its beneficial role protecting soils from erosion has been now questioned and several negative effects on soil and vegetation have been described. In this study we aimed to analyze the effects of *R. pseudoacacia* plantation on plant community composition and dynamics through the effects that *R. pseudoacacia* has on light, soil fertility and soil water availability. We used a chronosequence from 10–40-year-old plantations and compared the environmental and vegetation characteristics of that areas with that of natural control areas with similar age. The results showed that *R. pseudoacacia* plantations reached maturity around 30 years and then declined in density and canopy cover. We also found that soil nutrients and moisture at the superficial soil layer improved with age until maturity of plantations, but photosynthetically active radiation at the ground level and soil moisture at deeper soil layers decreased with maturity in relation to control conditions. Plots with *R. pseudoacacia* of all ages had higher cover values, lower number of species but higher β-diversity values than control conditions and they also differed in species composition. These differences in structure and species composition were related to the fertilizer effect of *R. pseudoacacia* that favored colonization by weeds and ruderal species, and to the light interception by the canopy of trees that exclude light-demanding species, most of them perennial herbaceous species which were the dominant species in control conditions.

1. Introduction

Afforestation is one of the most common technique used worldwide to prevent soil degradation and restore landscapes severely affected by soil erosion (Nunez-Mir et al., 2015). Sometimes, however, afforestation has unexpected negative effects, such as plant invasion (Weber, 2003; Cierjacks et al., 2013), biodiversity impoverishment (Sitzia et al., 2012; Trentanovi et al., 2013), no positive effects on control of soil erosion (Kou et al., 2015), the issue of forest fires (Mataix-Solera et al., 2011; Pereira et al., 2015). It has been an intense matter of debate (Le Houerou, 2000; Cao et al., 2011).

The black locust or false acacia (*Robinia pseudoacacia* L., Leguminosae), is a broad-leaved, light-demanding, medium-sized pioneer and a nitrogen fixing tree (Gilman and Watson, 1994; Bolat et al., 2015). *R. pseudoacacia* was introduced for afforestation from its native range in south-eastern North America to other areas of North America and in temperate South America, northern and southern Africa, temperate Asia, Europe, Australia and New Zealand (Weber, 2003; Sitzia et al., 2012), where it has undergone rapid expansion and became in many places an invasive plant (IUCN; Cierjacks et al., 2013). It is one of the most widely-planted tree species in the world after several Eucalyptus and Poplar species (Boring and Swank, 1984; Degomez and Wagner, 2001) and it is cultivated worldwide because of the high-quality timber properties, because of its ability to grow under different soil and climatic conditions and its tolerance to drought and erosion (Böhm et al., 2011; Cierjacks et al., 2013). Natural reproduction of the black locust is primarily vegetative through root suckering and stump

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sprouting allowing them to regenerate vigorously after coppicing and perturbations (Zhou and Shangguan, 2005).

Due to its transitional geographic position and climate, complex topography and high degree of human activity, the hilly and gully region of the northern Loess Plateau has become the most eroded region, and one of the most vulnerable areas to desertification in China (Fu et al., 2011). The primary approach for solving these problems has been vegetation restoration (Zheng, 2006), considered to be an effective strategy to combat soil erosion and soil degradation, and to restore the ecological integrity of disturbed ecosystems (Cerdà, 1997; Jiao et al., 2012). In this context, *R. pseudoacacia* was considered a promising tree for afforestation due to its fast growth and its ability to fix atmospheric nitrogen, and it was first introduced into the Loess Plateau in 1950s when the Chinese government launched large scale tree planting campaigns to revegetate the denuded mountains in this region (Guo et al., 2005; Jiao et al., 2012). Later, in 1999, the Chinese government implemented the "Grain for Green" policy (conversion of steep cultivated land to forest and grassland) to control soil erosion, and again *R. pseudoacacia* was widely used for this purpose with the result that more than 70,000 ha were afforested with this species from 1950 to 2005 in the hilly Loess Plateau (Guo et al., 2005). However, in the past years, several negative effects of *R. pseudoacacia* plantations on soil properties have been described, questioning its beneficial role (Jiang et al., 2013; Zhu et al., 2015).

The effect of the *R. pseudoacacia* plantation on soil properties in this area have been extensively studied by many authors. Soil structure (Wang et al., 1995; Dai et al., 2008), soil chemical properties (such as soil cation exchange capacity, organic carbon, total nitrogen, nitrate) (Qiu et al., 2010; Zheng et al., 2011; Wang et al., 2012), soil respiration (Xue et al., 2007), soil enzyme activity (such as alkaline phosphatase and invertase) and microbial biomass (Wang et al., 2012) improved in relation to control soils. However, other studies shown that *R. pseudoacacia* strongly deprives water from soils in the stands where it has been planted (Li, 2001; Wang et al., 2008), leading to the formation of a "soil dry layer" in depth, and thus becoming an important ecological hazard for other organisms and for water recharge of the water table (Chen et al., 2008; Li et al., 2010). Given that most of these studies differed in the age of plantations studied or they lacked comparison with controls of the same age, and given that some studies suggested that the effects on soil properties can vary with age of plantations (Qiu et al., 2010), we used a design that included at the same time both, time from plantation and controls to fully understand the effects of black locust on soil properties.

Significantly, to date, researchers have been put the attention more on the effects that *R. pseudoacacia* has on soil properties of these hilly areas in the Loess Plateau than on its effects on biodiversity and vegetation of the area, and then in the services that this ecosystem provides to the local people communities (Liu, 2008; Kou et al., 2015). In its native range and also in other places where mature vegetation is dominated by shade-tolerant trees, the black locust is an important early step in forest succession because of its ability fixing nitrogen and providing shade that promotes the establishment and growth of late successional tress (Boring and Swank, 1984; Cierjacks et al., 2013). Later, these trees suppress black locust saplings because of competition for light (Motta et al., 2009; Cierjacks et al., 2013). Because vegetation of the hilly areas of the Loess Plateau lacks of shade-tolerant trees and it is dominated by steppe plants, mainly of the Poaceae, Asteraceae and Leguminosae families (Jiang et al., 2013), *R. pseudoacacia* may have important consequences for the dynamics and composition of plant communities through the reduction of light availability.

The objective of our study is to analyze the effects of *R. pseudoacacia* plantation on plant community composition structure and dynamics in the hilly eroded areas of the Loess Plateau in China through the effects that *R. pseudoacacia* has on light availability, soil fertility and soil water availability. We used a chronosequence from 10 to 40 years old plantations and compared the environmental and vegetation characteristics of that areas with that of control areas with similar age from abandonment of agricultural practices. The results that we obtained are discussed in relation to the use of trees on afforestation of degraded areas in the Loess Plateau.

2. Materials and methods

2.1. Study area

The study took place in the Zhifanggou, Songjiagou and Heta watersheds (109°15′N, 36°44′E), which are located in the Yan river basin, North Shaanxi Province, China (Fig. 1). The altitude ranges from 1010 to 1430 m a.s.l. Soils (yellow-brown soil) are derived from very homogeneous loess sediments and are typically composed of approximately 64% sand (50–2000 μm), 24% silt (2–50 μm), and 12% clay (<2 μm) (USA soil taxonomy) (Wang et al., 2009). Due to the loose soil particles and the poor resistance, the soil is prone to severe erosion processes (Shi and Shao, 2000). The climate is temperate and semi-arid. Average annual precipitation, evaporation, temperature are 504 mm, 1000 mm and 8.8 °C, respectively (Zhang et al., 2011). Due to the basal topography and modern rates of erosion, the geomorphology of the watershed is characterized by various types of broken terrain, including hilly land (35%), gully slopes (61.5%) and gullies (3.54%).

The area belongs to the steppe ecotone between forest and grassland. Current land uses include croplands, forests, shrub lands, grasslands and residential areas in a mosaic pattern (Jiao et al., 2012). Croplands are mainly grain crops and orchards. Forest is composed by the *R. pseudoacacia* plantations. Shrub lands are dominated by some native shrub species, such as *Sophora viciifolia*, *Periploca sepium*, *Rosa xanthina*, *Spiraea pubescens* and also by some introduced species, such as *Caragana intermedia* and *Hippophae rhamnoides*. Grasslands are composed of herbaceous and small shrub species, such as *Artemisia scoparia*, *Lespedeza davurica*, *Stipa bungeana*, *Artemisia giraldii*, *Artemisia gmelinii* and *Bothriochloa ischaemun*.

Because of the accumulative effect of *R. pseudoacacia* plantations on environmental variables with age (e.g. over-shading, N accumulation), sample areas were selected from recently *R. psudoacacia* plantations to the oldest we could find in the area (40 years old), and control areas of similar age. Age classes every 10 years were chosen, from class 10 years (plots planted 10 years ago at the moment of sampling) to class 40 (plots planted 40 years ago). As *R. psudoacacia* plantation and control areas we used old cropland areas in the same watersheds. The major crops were potatoes (*Solanum tuberosum*), beans (*Phaseolus vulgaris*), buckwheat (*Fagopyrum esculentum*), and millet (*Panicum miliaceum*). Control areas followed spontaneous succession after that cultivation ceased (Jiang et al., 2013). After cropland abandonment annual plants (i.e. *A. scoparia*) colonize first these areas but they gradually decrease five or six years later and became invaded by perennial herbs, such as *L. davurica*, *S. Bungeana*, *B. ischaemun* and *A. gmelinii*. These herbaceous communities had relatively complex structure and high biological diversity, and maintain forming permanent grassland. Sometimes, shrub species like *S. viciifolia* gradually invaded the grassland communities but without becoming dominant species (Jiao et al., 2007; Kou et al., 2015).

Age of plantations and time since abandonment of control areas were obtained from interviews with local farmers and they were contrasted with records registered in the An'sai Ecological Experimental Station of Soil and Water Conservation. All the

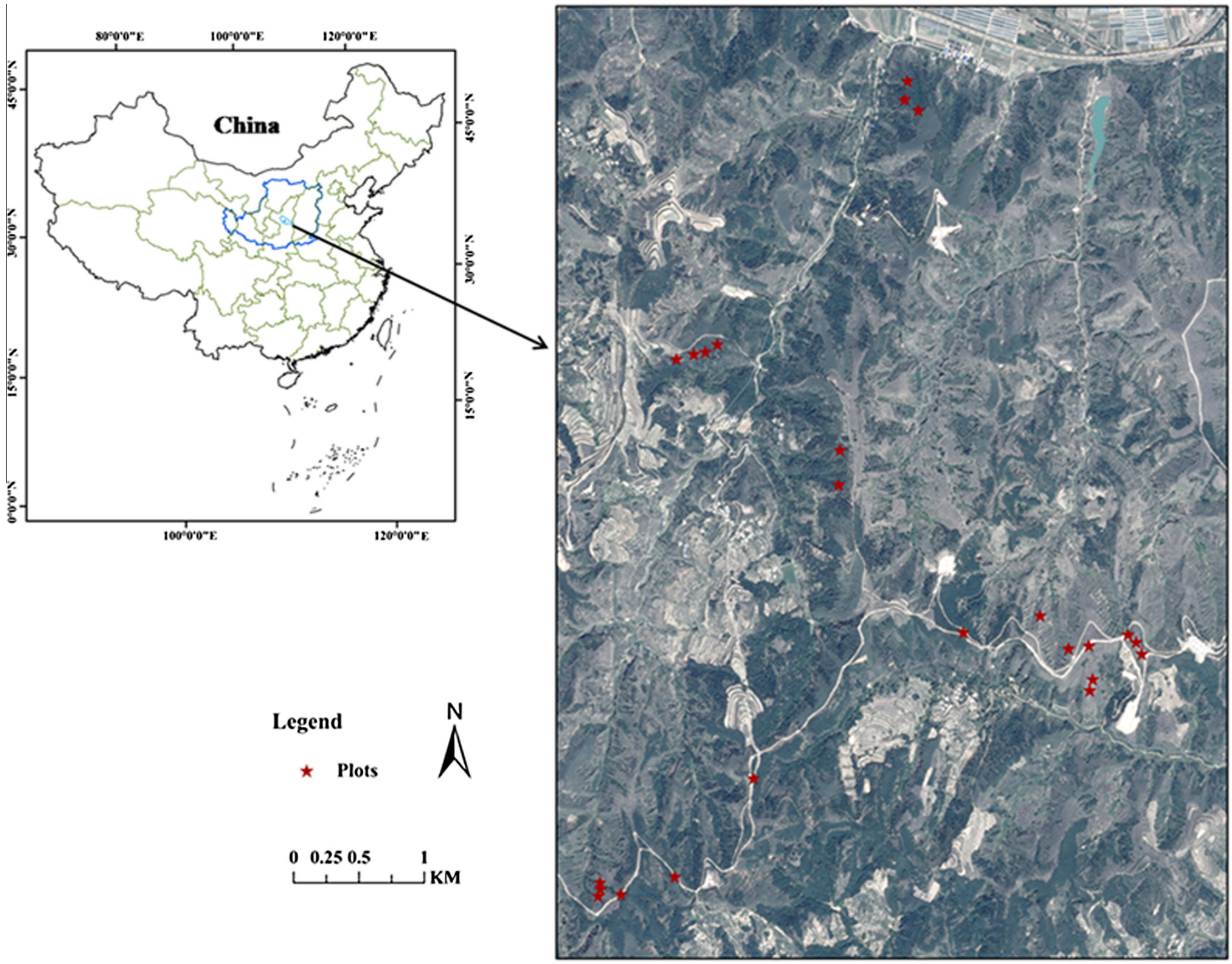

Fig. 1. Location of study area sampling plots.

R. pseudoacacia plantations had been planted with a layout of 2 m × 2 m resulting in similar initial tree densities in all stands. Plantations and control areas were all south-oriented and they had a 25–40 of slope angle. We selected three areas per age and treatment level and one 10 m × 10 m plot was used to take the samples and obtain the data in each area. In total we used 24 plots (see Fig. 1 for the location of the plots). We refer them as Robinia and Control plots hereafter. Fig. 2 shows photos of Robinia and Control plots.

2.2. Environmental variables

Photosynthetically active radiation (PAR) was measured in each plot between July and August of 2015 with a radiometer (Field Scout Quantum light meter, 3415F, USA). We took five and nine randomly PAR measures per plot in the Control and Robinia plots, respectively, from 10:00 a.m. to 14:00 p.m. at about 35 cm height from the soil surface.

Soil samples were taken in the plots at the same time that we performed the vegetation survey. We selected three randomized points in each plot and took samples from 0 to 100 cm depth by using an auger. We determined soil properties at three depths: 0–5 cm, at which is the depth that most of the seeds germinate and seedlings first obtain water and nutrients to growth; 5–60 cm, were most of the roots of herbs and small shrubs concentrate; and 60–100 cm, the depth that roots of most shrubs and trees can reach. We measured soil organic content (SOC) and the availability of the most limiting nutrients for plant growth (available Nitrogen (aN) and available Phosphorous (aP)). Prior the chemical analyses, soil samples were air-dried and passed through 1 mm and 0.15 mm sieves respectively. Analyses were performed following the laboratory routine analytical method (Shang, 2010): SOC was measured by the $K_2Cr_2O_7$ method; aN was measured by using AA3 continuous flow analytical system method with 0.1 M KCl extraction and aP was measured by the colorimetric method with 0.5 M $NaHCO_3$ extraction.

We also measured soil moisture content in each depth once every month from April of 2015 to October of 2015 in two fixed points per plot with TDR sensors (TRIME-PICO-T3/IPH50, Germany).

2.3. Vegetation survey

Field vegetation surveys were performed in July and August of 2014 and 2015, respectively, when vegetation development reaches its annual maximum. The percentage of ground of the plots covered by vegetation was estimated visually by two or three observers walking the plots. Estimates were repeated in a plot

Fig. 2. Pictures of Robinia and Control plots.

when differences among observers were higher than 10%. In the Robinia plots, total vegetation cover and the cover by trees and by understory plants were recorded separately, and the height and diameter at breast height (DBH) of every tree in the plot were measured with a tape. In the control plots we recorded the total vegetation cover. We marked two 1 m × 10 m transects in every plot and recorded all the plant species present and estimated their frequency from its occurrence in every of the 1 m × 1 m quadrates of the two transects. All the species were assigned to one of the following growth-form types: annual, perennial herbaceous and woody (small shrubs, shrub and trees) and with this information we also determined the number of species of each growth form per plot. The total number of species that we found in these two transects was considered to represent the value of species richness of the plot, and we used it as a surrogate of α-diversity. We also measured the degree of differentiation among sites using species composition (β-diversity), which links species richness of sites (α-diversity) with species pool richness (γ-diversity) (Chase et al., 2011). As individual sites sample a smaller proportion of the total species pool they differ more markedly from one another and then, β-diversity increases. We chosen the Raup–Crick index (*vegdist* command, vegan package, R 3.1.4; R Core Team 2015) because it measures dissimilarity between the communities unbiased from the value of species richness of the sites compared (Chase et al., 2011).

2.4. Data analysis

Prior analyzing the effects of *R. pseudoacacia* plantations relative to control plots on environmental and vegetation variables, we analyzed the changes that happened with age of the plots on tree density, tree cover and tree size (DBH and height), using Linear Models (LM) with the *lm* command (stats package) and using stand age (10, 20, 30 and 40 years) as explanatory variable. We used graphical model validation to check for homoscedasticity and normality of residuals (Zuur et al., 2009).

The effect of *R. pseudoacacia* plantations and age on PAR, vegetation cover, species richness and the number of species of each growth form relative to Control plots were analyzed by using LMs. Also, LMs were used to analyze the effect of *R. pseudoacacia* plantations on the soil variables SOC, aN and aP but in this case we analyzed them separately for each soil depth, since we assume that these soil properties vary with depth. To analyze the effect of *R. pseudoacacia* plantations on soil moisture we analyzed each soil depth separately, as we did for the other soil variables, but in this case and since we also have repeated measures of soil moisture every month, we used Linear Mixed Models (LMM) with the *lme* command (nlme package), time as random factor and treatment and age as fixed factors. We cannot analyze the effects of *R. pseudoacacia* plantations and age on β-diversity with LMs because the index was calculated in relation to all the other plots and thus lack the necessary independence for the analyses. Instead, we used the *adonis* command (vegan package) that allowed us to perform multivariate LMs based on dissimilarity matrices and calculate the significance using permutation (we used 999 permutations).

Detrended correspondence analysis (DCA) with the Canonical community ordination (CANOCO) ordination program, version 4.5 (ter Braak and Šmilauer, 2002) was used to display plant community groups and their relationships in relation to species frequency.

3. Results

3.1. Variation of tree characteristics in the R. pseudoacacia plantations with age

Fig. 3 shows the variation with age of tree characteristics in the Robinia plots. Although all plantations had an initial planting density of 2300 trees ha^{-1}, tree mortality was high during the first years in all plots reaching a minimum density at age 10, with 1344.4 ± 204.2 tree ha^{-1} (X ± SE), then increasing tree density because of the recruitment of new individuals from root sprouts and seeds to reach a maximum of 2961.1 ± 344.5 trees ha^{-1} at year 30. From that time onwards, tree density decayed because of tree mortality and reached 1383.3 ± 120.2 trees ha^{-1} at year 40. The linear model explained 63.6% of the variance and was significant ($F_{3,8} = 7.397$; p-value = 0.0108). The post hoc comparison of tree density among ages revealed that only tree density at age 30 was significantly higher than density at age 10 (t = 4.128; *Pr*(>|*t*|) = 0.0033).

Tree cover of *R. pseudoacacia* increased from 47.6 ± 4.5% at age 10 to 60.3 ± 5.0% at age 20 and then decreased to a minimum of 43.8 ± 3.3% at age 40. The linear model explained a low proportion of the variance (42.3%) and it was marginally significant ($F_{3,8} = 3.689$; p-value = 0.0621). The post hoc comparisons indicated that only tree cover at age 20 was higher than age 10 (t = 2.339; *Pr*(>|*t*|) = 0.0475).

Both, height and DBH of *R. pseudoacacia* trees increased along the age series reaching a maximum of 9.7 ± 0.6 m and 12.1 ± 1.4 1.4 cm respectively at age 40, which significantly differed from that at age 10 (t = 4.330; *Pr*(>|*t*|) = 0.0025 and t = 3.140; *Pr*(>|*t*|) = 0.0138, respectively). The models explained 60.4% and 39.6% of the variance respectively, and models for both variables were significant ($F_{3,8} = 6.584$; p-value = 0.0149 and $F_{3,8} = 3.401$; p-value = 0.0738).

3.2. Effects of R. pseudoacacia plantations on soil nutrients

The values of SOC and aN were higher in Robinia plots than in Control plots at all depths (Fig. 4). In Control plots SOC increased

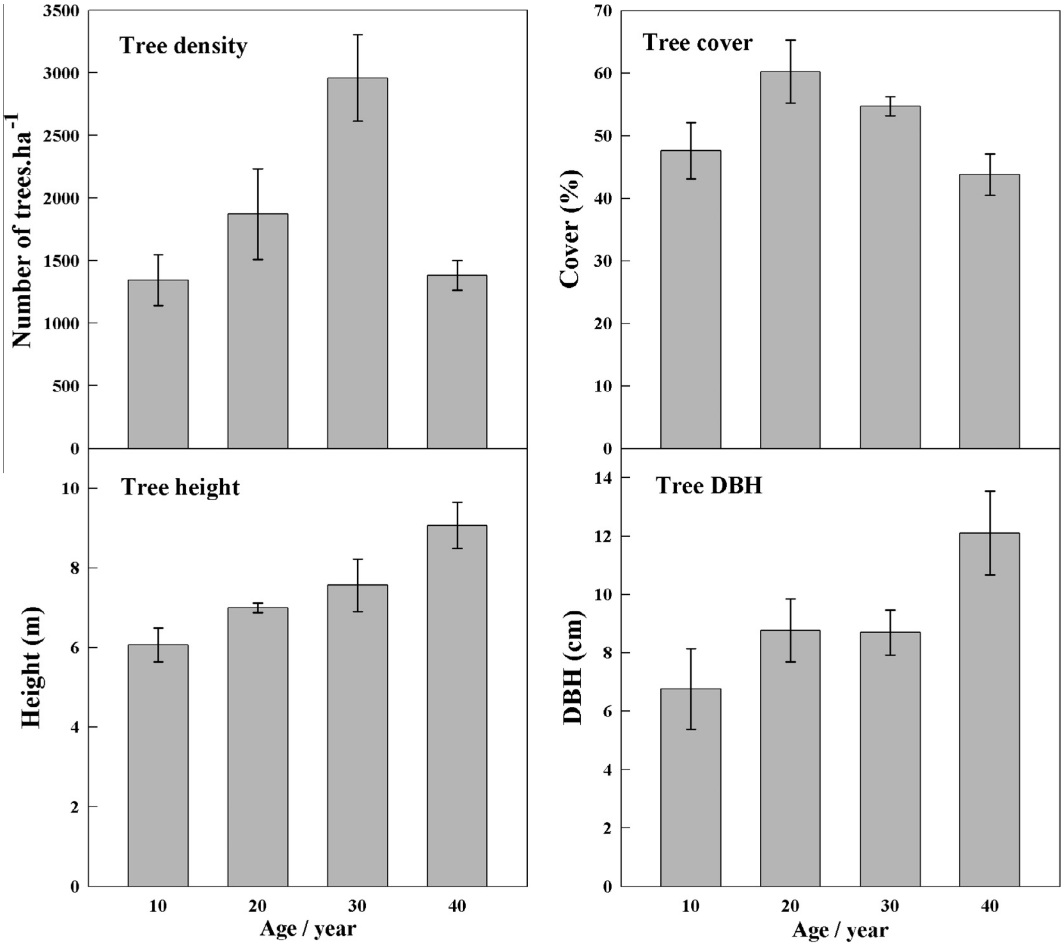

Fig. 3. Changes with age in tree variables of the plots afforested with *Robinia pseudoacacia*.

with age from 8.4 ± 0.2 to 15.4 ± 1.3 g kg^{-1} at 0–5 cm and from 5.9 ± 0.5 to 8.4 ± 1.0 g kg^{-1} at 6–60 cm, and maintained around 4.0 g kg^{-1} at 61–100 cm. In Robinia plots, SOC increased from 16.6 ± 3.4 g kg^{-1} at age 10 until 54.9 ± 11.4 g kg^{-1} at age 30 at 0–5 cm and then decreased, but at 6–60 cm and 61–100 cm SOC increased from 6.4 ± 0.1 and 2.9 ± 0.4 g kg^{-1} at age 10–12.2 ± 0.9 and 5.4 ± 0.8 g kg^{-1} at age 20 and then fluctuated around those values. The linear models of SOC for each depth explained 77.3%, 69.4% and 33.0% of the variance. The models for SOC at 0–5 cm and 6–60 cm were significant ($F_{7,16} = 12.2$; p-value < 0.0001 and $F_{7,16} = 8.45$; p-value = 0.0002) and in both models age and treatment and their interaction were significant, indicating that the trend of SOC with age differed between treatments. However, the linear model for SOC for 61–100 cm was not significant ($F_{7,16} = 2.62$; p-value: 0.0526).

Available Nitrogen in Control plots at 0–5 cm and 6–60 cm maintained with age around 10 mg kg^{-1}, but at 61–100 cm it decreased to 8 mg kg^{-1}. In Robinia plots, it increased with time until age 30 at 0–5 cm and 6–60 cm, reaching values of 41.5 ± 6.6 and 22.3 ± 1.7 mg kg^{-1}, respectively. From age 30 to 40 it decreased a little. At 61–100 cm it increased from age 10 to 20 and then maintained around 13.5 mg kg^{-1}. The models explained 65.7%, 73.0% and 30.6% respectively of the variance and, again, the models for 0–5 cm and 6–60 cm were significant ($F_{7,16} = 7.30$; p-value = 0.0005 and $F_{7,16} = 9.89$; p-value < 0.0001, respectively), but that for 61–100 cm was marginally significant ($F_{7,16} = 2.45$; p-value = 0.0655). At all soil depths, only the plantation treatment was significant, indicating the important contribution of the plantation of *R. pseudocacia* to aN amount of the soils relative to the contribution of age.

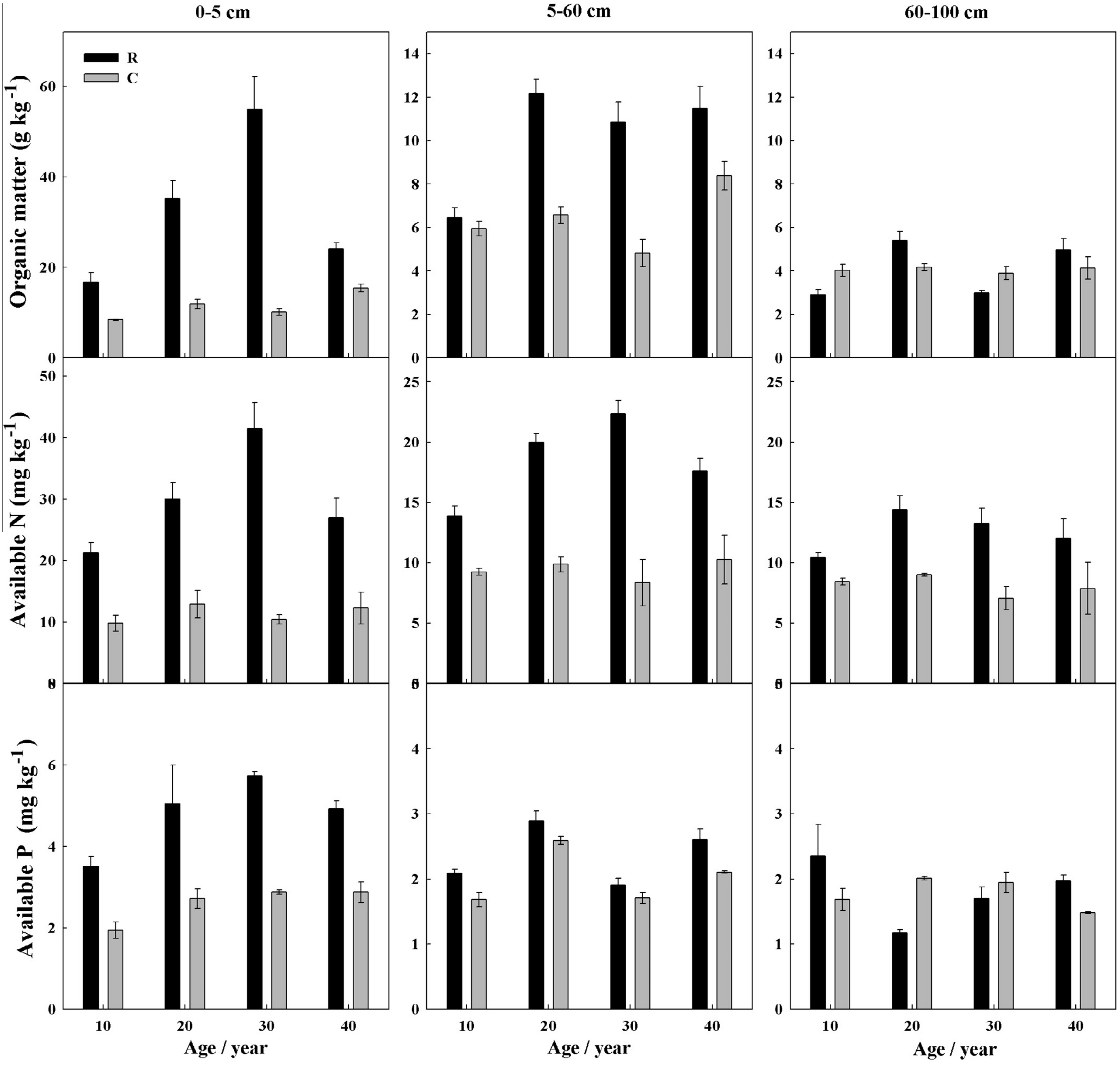

Fig. 4. Changes with treatment and age of the plots in fertility parameters at different soil depths. R: Robinia plots; C: Control plots.

Available phosphorous was only a few higher in Robinia than in Control plots at all depths (average 3.15 ± 0.34 mg kg^{-1} for Robinia plots and 2.35 ± 0.17 mg kg^{-1} for Control plots, respectively). In Robinia plots at 0–5 cm aP increased from 3.51 ± 0.36 to 7.63 ± 1.90 mg kg^{-1} from age 10 to 30 and then decreased to reach 4.95 ± 0.52 mg kg^{-1} at age 40. Linear models of aP for 0–5 cm and 6–60 cm were significant and explained 36.7% and 42.2% of the variance respectively, but only the treatment effect in the 0–5 cm

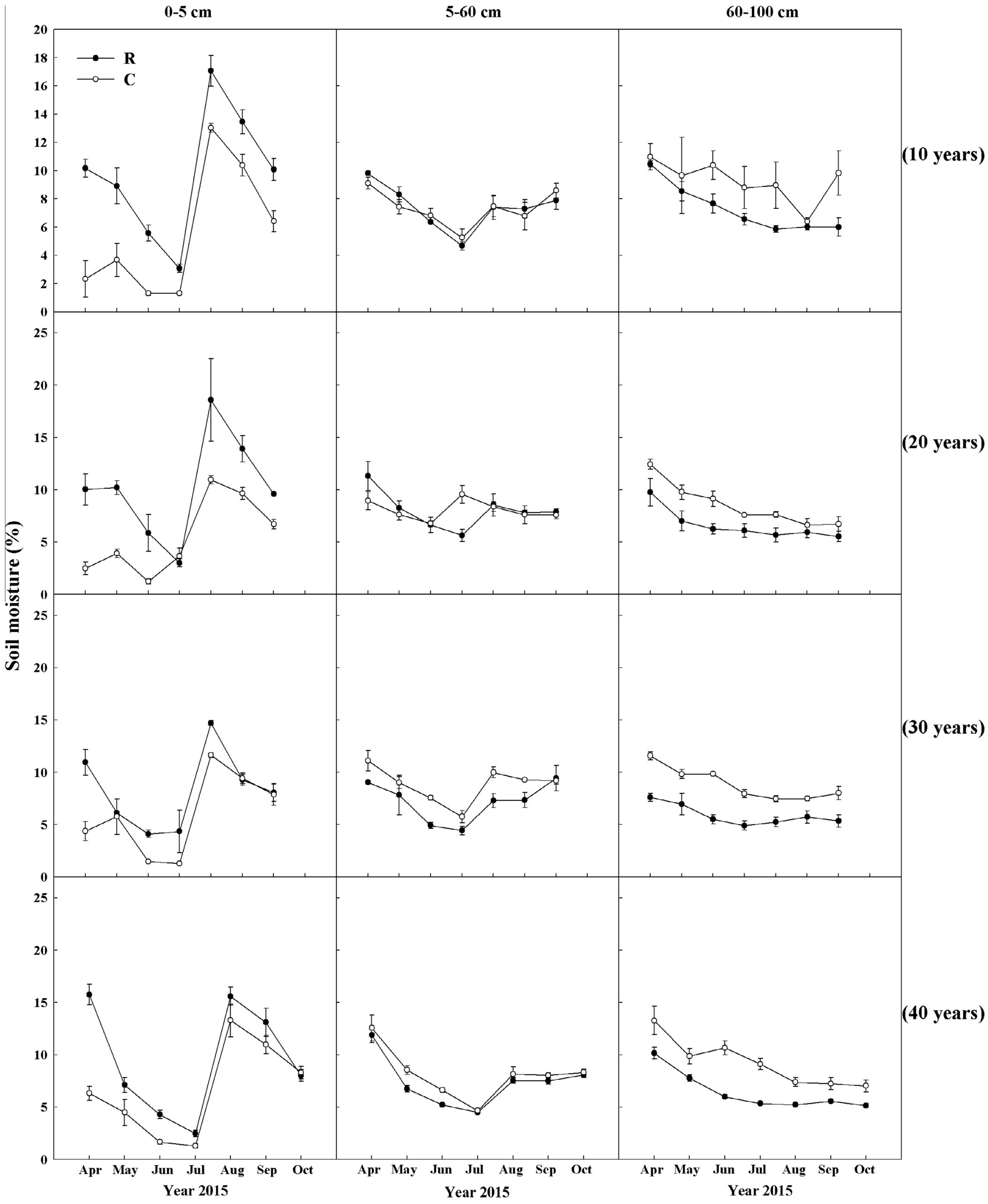

Fig. 5. Soil moisture dynamics at different ages and soil depths along the sampling period. R: Robinia plots; C: Control plots.

model and age in the 6–60 cm model were significant ($F_{1,16} = 10.71$; p-value = 0.0048 and $F_{3,16} = 6.57$; p-value = 0.0042, respectively). The linear model for aP at 61–100 cm was not significant ($F_{7,16} = 0.90$; p-value = 0.5304) and explained almost nothing on the aP variation (0.03%).

3.3. Effects of R. pseudoacacia plantations on soil moisture

Fig. 5 represents soil moisture dynamics at different depths of plots from April to October 2015 in relation to *R. pseudoacacia* plantation and age. As expected, the more superficial the soil layer, the stronger was the fluctuation in soil moisture along the seasons. The most superficial soil layer responded very fast to the rainfall during the monsoon rainfall in August and also to the desiccating atmosphere caused by high air temperatures and sun radiation in summer. At deeper soil layers moisture was higher at the beginning of the spring, but soils were drying along the late spring and summer to recover only a little during the monsoon rainfalls and then maintained their moisture levels until the end of the study period. Differences in soil moisture content between treatment levels were greater in the most superficial layer than in the deeper ones. At the deepest soil layer (61–100 cm) moisture content of Control plots was higher than that of Robinia plots along the entire time series but the inverse occurred in the more superficial layer (0–5 cm), where soil was dryer in Control than in Robinia plots. At intermediate soil depth (6–60 cm) soil moisture of Control plots at ages 10 and 20 was lower than that of Robinia plots, but at ages 30 and 40 it was higher. In Control plots at 0–5 cm soil moisture increased a little with age from 5.51 ± 1.22% at age 10 to 6.95 ± 0.47% at age 40 and in Robinia plots it maintained around 9% in the same age range. At depths 6–60 and 61–100 cm, soil moisture in plots of both treatment levels were lower than in the most superficial layer and it decreased somewhat with age.

The linear mixed model for soil moisture at 0–5 cm depth explained 79.6% of the variance indicating that soil moisture was significantly affected because of the treatment ($F_{1,107} = 65.86$; p-value < 0.0001), but not by age and their interaction, thus confirming the protective role of *R. pseudoacacia* on soil evaporation at the soil surface level. The linear model showed that both, age and treatment and their interaction significantly influenced soil moisture at 6–60 cm depth (age: $F_{3,112} = 7.91$; p-value = 0.0001; treatment: $F_{1,112} = 7.23$; p-value = 0.0083; interaction: $F_{3,112} = 3.63$; p-value = 0.0152), confirming the different soil moisture dynamics with age between Control and Robinia plots. At 61–100 cm soil moisture was affected significantly because of the age and the treatment but was not affected because of their interaction, confirming the lower moisture of soil in the Robinia plots at all ages.

3.4. Effects of R. pseudoacacia plantations on vegetation cover and PAR

The total vegetation cover in Control plots increased continuously from age 10 to age 40, growing from 35.4 ± 2.9% to 66.3 ± 4.5% (Fig. 6). In Robinia plots, vegetation cover at age 10 was 74.3 ± 3.1%, twofold that of the Control plots, then increasing to reach 80.4 ± 2.1% at age 20. From age 20 onwards, it decreased sharply to reach less than 60% at age 40. The linear model explained 75.8% of the variance of the vegetation cover and was significant ($F_{7,16} = 11.27$; p-value < 0.0001). Treatment and the interaction term, but not age were significant, indicating that the trend of vegetation cover with time differed between treatments but the extent of these differences varied with age. When we analyzed the vegetation cover excluding that provided by the *R. pseudoacacia* trees (data not shown), we found that vegetation cover in Robinia plots decreased with time except for age 40 when it increased a lot to reach a value that is between ages 10 and 20. The linear model explained 74.8% of the variance and was significant too ($F_{7,16} = 10.77$; p-value < 0.0001), with all terms significantly affecting the response variable. The interaction term contributed the most to the model (45.3%) indicating that the trend with time of the vegetation cover without trees differed between treatments.

Photosynthetically Active Radiation (PAR) was very different in Control plots than in Robinia plots as expected, because of the differences in vegetation cover between treatments. It decreased

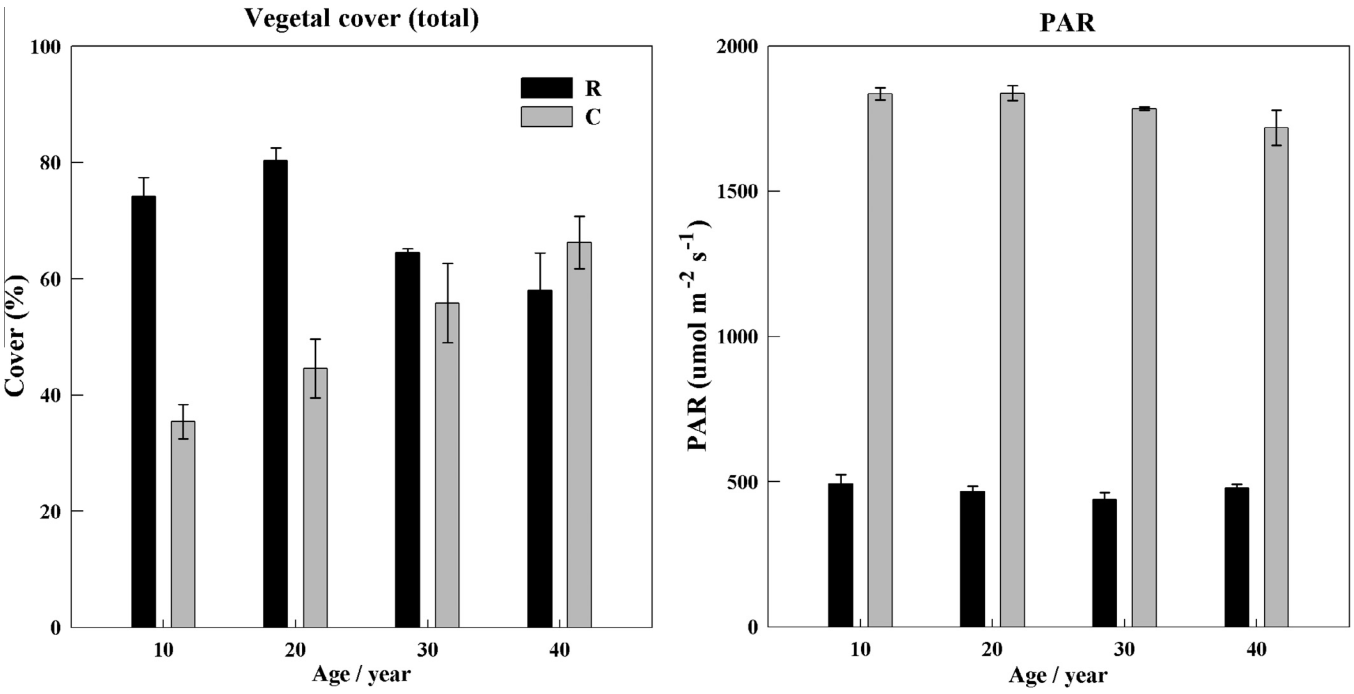

Fig. 6. Changes with treatment and age in vegetation cover and Photosynthetically Active Radiation (PAR) parameters of the plots. R: Robinia plots; C: Control plots.

continuously in Control plots from 1835.47 ± 35.64 μmol m^{-2} s^{-1} at age 10 to 1719.07 ± 104.76 μmol m^{-2} s^{-1} at age 40. In Robinia plots it first decreased from 492.48 ± 54.66 μmol m^{-2} s^{-1} at age 10 to 437.67 ± 42.84 μmol m^{-2} s^{-1} at age 30 and then, at age 40 it reached a value near the value at age 10 (Fig. 6). However, the linear model explained near all the variation of PAR (99.4%) and it was significant ($F_{7,16} = 578$; p-value: <0.0001), indicating that only treatment but not age and their interaction significantly affected PAR.

3.5. Effects of *R. pseudoacacia* plantations on species composition

We recorded 76 species in the plots, 50 of them in Robinia plots and 52 in Control plots. Twenty-six species were shared by both, the Robinia and the Control plots, and 24 and 26 species were exclusive of Robinia and Control plots, respectively. Compositae, Poaceae and Leguminosae were the plant families most represented in the plots and accounted for 25.0%, 22.4% and 14.5% of the total of the species.

Ordination analysis (Fig. 7) revealed differences in species composition because of the *R. pseudoacacia* plantations (Axis I) and age (Axis II) and showed that changes in species composition with age were greater in Robinia than in Control plots. Both axes absorbed 80% of the total variation in species composition of the plots (Axis I: 50% and Axis II: 30%). Interestingly, species composition in Robinia plots at age 40 resembled most the composition of Control plots than at any other age. In the *R. pseudoacacia* stands, the dominant species at age 10 were the annual weed and ruderal species *Setaria viridis*, *Bidens tripartita*, *Salsola ruthenica* and *Artemisia scoparia*. In the next decade, the herbaceous perennial species *Stipa bungeana* and *Achnatherum splendens* became the dominant species, *S. ruthenica* and *A. scoparia* disappeared and the shade-tolerant species *Periploca sepium*, *Rubia cordifolia* and *Viola dissecta* started colonizing the plots. At age 30, the annual weeds *Solanum nigrum* and *Melica scabrosa* were the dominant species, *S. viridis* and *B. tripartita* disappeared and *P. sepium*, *R. cordifolia* and *V. dissecta* became very frequent. The sub-shrubs *Artemisia giraldii* and *Lespedeza davurica* were very important at age 40, when the also sub-shrub *Artemsia gmelinii* became the dominant species. In the Control plots, the light-demanding herbaceous species *L. davurica*, *S. bungeana*, *Heteropappus altaicus*, *A. gmelinii*, *A. scoparia* and *Cleistogenes squarrosa* dominated at age 10. In the next decade, the also shade-intolerant perennial herbaceous species *Bothriochloa ischaemun*, *Cleistogenes chinensis* became dominant but *Heteropappus altaicus* and the annual *A. scoparia* disappeared. At age 30, the also light-demanding herbaceous species *Roegneria kamoji* and *Astragalus melitoloides* became the dominant but *C. squarrosa*, *B. ischaemun* and *C. chinensis* became company species. The lesser light-demanding herb *Vicia sepium* appeared as a main species at age 40 and *L. davurica* and *S. bungeana* became company species. Some

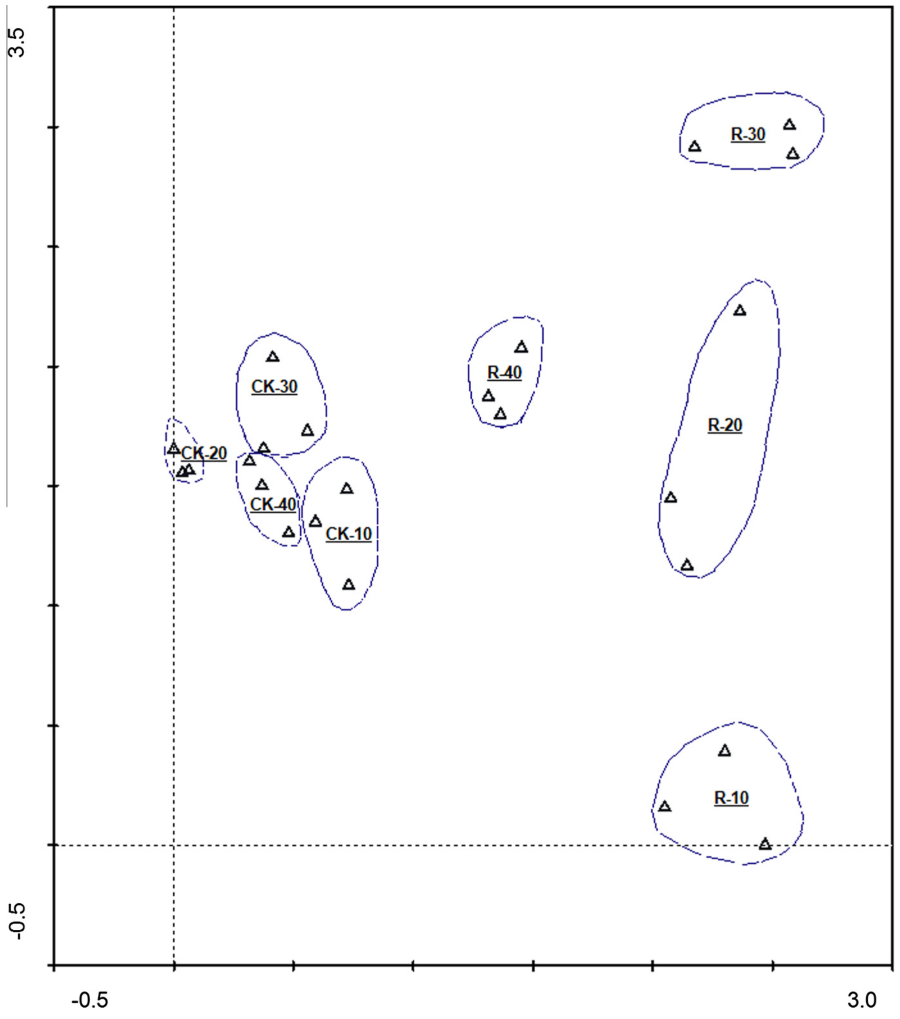

Fig. 7. DCA community-site ordination diagram. Total variation in species composition explained by the two axes was 80% (50% axis I and 30% axis II). R: Robinia plots; C: Control plots. The numbers 10, 20, 30 and 40 indicate the age of the plots.

species, such as *A. gmelinii*, *L. davurica* and *S. bungeana* appeared in plots of all ages, but they changed their frequency with age.

3.6. Effects of R. pseudoacacia plantations on species richness and β-diversity

Fig. 8 displays the values of species richness (total, annual, herbaceous perennials and woody species) in relation to treatment and age. Species richness increased with time in Control plots from 17.3 ± 0.9 to 22.7 ± 1.9 sp 20 m^{-2}, and also Control plots were richer in species than Robinia plots. In Robinia plots the number of species per plot increased irregularly. At age 10 there were 16.3 ± 1.9 sp 20 m^{-2}, then increased at age 20, decreased at age 30 and increased again at age 40, when reached its maximum with 19.7 ± 0.9 sp 20 m^{-2}. The linear model explained 28.5% of the variance and was marginally significant ($F_{7,16} = 2.31$; p-value = 0.0783) and only the treatment significantly affected species richness ($F_{1,16} = 5.64$; p-value = 0.0303).

The number of annual species followed a different pattern than species richness. It decreased continuously with age in Robinia

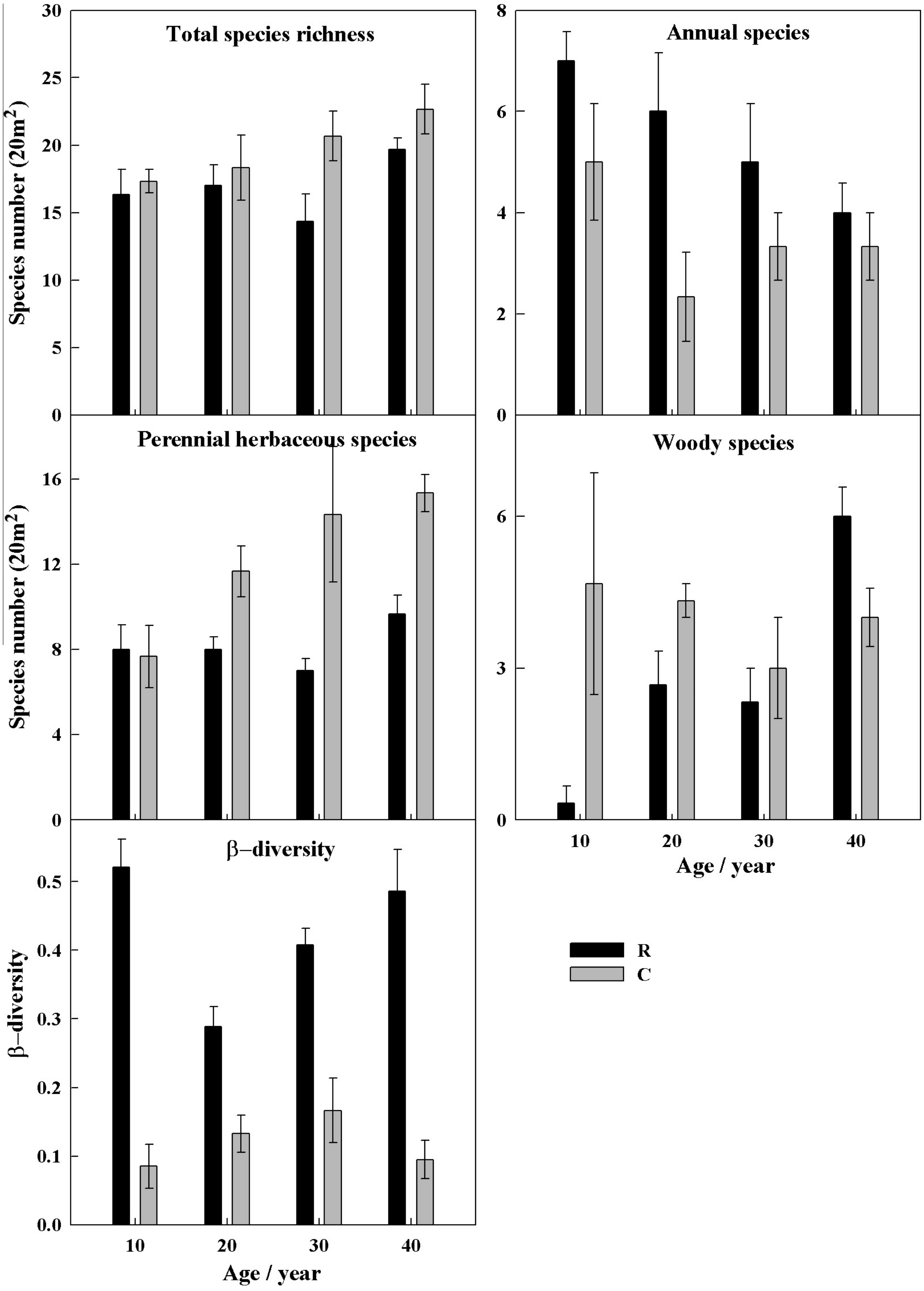

Fig. 8. Changes in total species number and species number of the different growth forms, and β-diversity (Raup-Crick index) in the plots because of treatment and age. R: Robinia plots; C: Control plots.

plots from 7.0 ± 0.6 to 4.0 ± 0.6 sp 20 m^{-2}, but in Control plots it fluctuated between 2.3 ± 0.9 and 5.0 ± 1.1 sp 20 m^{-2} along the age series. The model explained 37.9% of the variance and was significant ($F_{7,16} = 3.01$; p-value = 0.0323), indicating that Robinia plots had more annual species than Control plots and this effect was independent of the age of plots.

The number of perennial herbaceous species increased strongly with age in Control plots from age 10 to 40, from 7.8 ± 0.8 to 15.3 ± 0.9 sp 20 m^{-2}. And it maintained near 8 sp 20 m^{-2} in Robinia plots from age 10 until age 30, and then increased to 9.7 ± 0.9 sp 20 m^{-2} at age 40. The linear model explained 53.6% of the variance and it was significant ($F_{7,16} = 4.79$; p-value = 0.0045) showing that age and treatment, but not the interaction between them, significantly affected the number of perennial herbaceous species in the plots. Treatment was the most influential factor, with 46.2% of the explained variance, and age had a minor influence; indicating that there was more herbaceous perennial species in Control than in Robinia plots and that its value increased with time in both treatment levels.

The number of woody species in Control plots was maintained with time and fluctuated from 3 to 4.5 sp 20 m^{-2} but in Robinia plots it increased with time from 0 sp 20 m^{-2} at age 10 to 6.0 ± 0.6 sp 20 m^{-2} at age 40. The linear model explained 39.6% of the variance and was significant ($F_{7,16} = 3.15$; p-value = 0.0271) but only the interaction between age and treatment was significant, indicating that the number of woody species in plots followed different patterns between treatments.

There were huge differences in β-diversity between Robinia and Control plots. In average, β-diversity values of Robinia plots were many times greater than that of Control plots, indicating that among Robinia plots there were higher differences in species composition than among Control plots, which were more homogeneous. The model explained almost all the variation (98%) and both factors and their interaction had a significant influence on the β-diversity values (Pr(>F) < 0.0001 in all cases), but the treatment was the most contributing factor explaining the variations of β-diversity (58.8%), whereas age and the interaction had lower importance (20% and 19% respectively).

4. Discussion

Our research showed that *R. pseudoacacia* plantations in the studied area reached maturity around 30 years, similar to that found in other studies in the area (Wang et al., 2012), when they attained their maximum canopy cover and tree density. After that, plantations declined in both canopy cover and tree density, and the surviving trees still continued growing in size, presumably thanks to the reduction in intraspecific competition, as occurs in its native range and some places where the species has been introduced (Boring and Swank, 1984; Cierjacks et al., 2013; Enescu and Dănescu, 2013). Paralleling these changes, *R. pseudoacacia* modified the environment in the areas where the species was planted. So, at the ground level PAR decreased and at the superficial soil layer nutrients increased until plantation maturity, then decreasing as reported in other research in the area (Qiu et al., 2010). At deeper soil depths, the amount and variations with age of SOC and available P were smaller than that at 0–5 cm depth, but available N that had very similar values across the entire soil profile and also followed the same trend with the superficial soil layer, as expected from the ability of this species capturing atmospheric N through its deep root system (Dzwonko and Loster, 1997; Von Holle et al., 2006). Soil moisture content showed a consistent decrease with age at all soil depths until maturity of plantations and then maintained a constant value, suggesting that the reduction in water consumption because of the decrease in tree density and canopy cover from age 30 was compensated by the increased growth of the remaining trees (Giuggiola et al., 2015). The use of true replicate plots for all ages and treatments in this research confirmed and broadened the previous findings that *R. pseudoacacia* reached their mature stage around age 30 in the Loess Plateau and that the impact on soil nutrients, soil moisture and PAR of these plantations intensified until the maturity of the plantations (Jin et al., 2011; Cheng et al., 2013, 2014). Likewise, our results indicate that both the fertilizer effect of *R. pseudoacacia* due to the N fixing ability and the reduction in soil moisture content, were maintained along the soil profile until at least several years after the maturity of the plantations, and that it happened despite the declining in canopy cover and tree density that plantations of *R. pseudoacacia* experienced after maturity.

In relation to what occur in the control areas, our results showed that the amount of PAR reaching the ground was an order of magnitude higher in Control plots than in Robinia plots and it was independent of the age of abandonment. Available N at all soil depths were lower in Control plots than in Robinia plots at all ages in coherence with the mentioned ability of *R. pseudoacacia* to fix atmospheric N through its roots and in agreement with previous results (Qiu et al., 2010; Bolat et al., 2015; Buzhdygan et al., 2016). In relation to soil moisture content and available P, Control plots were also dryer and poorer respectively than that of Robinia plots only at the upper soil layer, accordingly to the protective effect of the canopy on soil evapotranspiration, its higher production of labile vegetal debris and its faster mineral cycling (Wang et al., 2012). At deeper soil layers instead, *R. pseudoacacia* had no effect on available P but it had a negative effect on soil moisture that was stronger in the older plots, presumably because of the increase in soil water consumption by trees, as reported by Shangguan (2007) and that can explain the lower runoff water amounts observed in afforested watersheds (Huang et al., 2003; Huang and Zhang, 2004). Since soil water is a key factor limiting vegetation growth in the hill-gully region of the Loess Plateau, large-scale tree plantations can then increase the severity of soil water shortages and the risk of desertification (Cao et al., 2007, 2011). In this study we only measured soil moisture until 100 cm but some researchers measuring until 500 cm found that 0–140 cm was the soil moisture active layer in this type of soils (Shangguan, 2007). Those studies also showed that *R. pseudoacacia* roots can reach a depth near 10 m deep and that a stable soil dry layer was formed at 200–1000 cm (Mu et al., 2003; Shangguan, 2007; Wang et al., 2008) whose moisture content is very difficult to increase. In our study, we found that, even after the heavy rainfall period in 2013 (1071 mm from May to October), the infiltration depth of soil under the 30 years *R. pseudoacacia* plantation was only about 300 cm, while under grassland vegetation the moisture recharge reached 500 cm in depth (Yin et al., 2015).

In relation to vegetation variables, our results showed that *R. pseudoacacia* plantations caused important effects on vegetation cover, diversity and composition of plant communities, and that these effects were stronger enough to exceed the effects that plant succession –using age as a surrogate- had on these variables. So, Control plots and Robinia plots had different species composition, but Control plots of all ages had lower cover values but higher number of species than Robinia plots, mainly of herbaceous perennial species that contributed most to the soil resistance to erosion (Zhu et al., 2015), and also Control plots of the same age were more homogenous in composition than Robinia plots, accordingly with the values of β-diversity. These differences between Control and Robinia plots may be the consequence of the effects that *R. pseudoacacia* plantations have on micro-environmental conditions. So, species richness and the number of herbaceous perennial species correlated positively with PAR (r = 0.4460, p-value = 0.0289; and r = 0.6438, p-value = 0.0007 respectively) and also the number of herbaceous species correlated negatively with soil nitrogen at all depths (r = 0.5303, p-value = 0.0077 at 0–5 cm; r = 0.4925, p-value = 0.0148 at 6–60 cm; and r = 0.4136, p-value = 0.0443 at 61–100 cm). However, β-diversity did negatively correlated with PAR (r = −0.7108, p-value < 0.0001) and positively with the total soil moisture content at the upper soil layer (r = 0.7486, p-value = 0.0326) and with available Nitrogen content along the entire soil profile (r = 0.5929, p-value = 0.0023 at 0–5 cm; r = 0.6156, p-value = 0.0014 at 6–60 cm; and r = 0.4816, p-value = 0.0172 at 61–100 cm). These results indicate that light interception by *R. pseudoacacia* has a negative effect on the number of species living in the plots but also that the effects of *R. pseudoacacia* varied among plots, possibly because the among plot differences in tree density and distribution, thus enhancing the differences in environmental heterogeneity of plots and providing opportunities for different ruderal and shade-tolerant species to colonize them. These changes because of the introduction of *R. pseudoacacia* are coherent with those results reported in the literature (Sitzia et al., 2012; Trentanovi et al., 2013). However, similar consequences in the studied area were found after afforestation with the exotic shrub *Hippophae rhamnoides*, which forms thick dense canopies that exclude light-demanding species (Jiang et al., 2003). In coherence with the decline of *R. pseudoacacia* in the older stands, species composition of Robinia plots at age 40 resembled more those of Control plots than at other ages, indicating that the effect of the *R. pseudoacacia* canopy on community composition decreased with the reduction in tree density and canopy cover that occur in Robinia plots after maturity.

One of the main objectives of afforestation with *R. pseudoacacia* in the hilly slopes of the Loess Plateau is protecting soil from erosion by wind and water (Jiao et al., 2012). Despite we have not addressed this subject in the present research, our data suggest that it cannot be longer assumed a general higher protective role of *R. pseudoacacia* plantations against soil erosion than natural vegetation. It is true that the amount of vegetation cover is directly related to soil protection from erosion (Jiao et al., 2012) and also that our results indicate that until age 20 total vegetation cover in Robinia plots was near two times higher than that of Control plots. However, vegetation cover in Robinia plots at plantation maturity and later was similar or even was lower than Control plots of the same age and Jiao et al. (2012) found that soil properties related to the susceptibility of soils to erosion at age 20 were not different between *R. pseudoacacia* stands and natural vegetation in the same study area. Furthermore, some researchers (Ji et al., 2012; Zhu et al., 2015) found that soil erosion rates of semi-arid grasslands in the Loess Plateau were inversely correlated to the functional diversity of communities based upon plant traits associated to root resistance to break and soil water infiltration, and that the plantations of *R. pseudoacacia* strongly reduced this functional diversity in relation to grasslands. They attributed this reduction mostly to the decline in perennial herbaceous species in the plots afforested with *R. pseudoacacia*, a reduction that we also found in our study.

5. Conclusion

In conclusion, we found that *R. pseudoacacia* development modified vegetation composition and structure in relation to control conditions mainly through its effects on light and soil moisture at the ground level and on soil nitrogen in the entire soil profile. However, these effects diminished once plantations reached maturation (around 30 years after planting). Our results also supported the view that *R. pseudoacacia* plantations have negative implications for water recharge of soils at depths that were of interest for water logging in the degraded areas of the Loess Plateau, and cautioned against the protective role of these plantations against soil erosion because their negative effects on perennial herbaceous species.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.05.025. These data include Google maps of the most important areas described in this article.

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Appendix I

Species list. Species are listed in family order. Species frequency is expressed as the percentage of each plot. The growth form codes are: A, annual plant; P, perennial herbaceous plants; W, woody plants (include shrub, subshrub and tree). The name of the species were cited from the *Flora of China*. R: Robinia plots; C: Control plots. The numbers 10, 20, 30 and 40 indicate the age of the plots.

Family	Species	Growth form	C-10-1	C-10-2	C-10-3	C-20-1	C-20-2	C-20-3	C-30-1	C-30-2	C-30-3	C-40-1	C-40-2	C-40-3	R-10-1	R-10-2	R-10-3	R-20-1	R-20-2	R-20-3	R-30-1	R-30-2	R-30-3	R-40-1	R-40-2	R-40-3
Valerianaceae	*Patrinia heterophylla*	P		10					10	70	60	10	30	20					25	20		5				
Labiatae	*Dracocephalum moldavica*	A	40		20	5			10	10		30		40		50	45									
	Leonurus artemisia	A																	40					5	5	10
Leguminoseae	*Glycyrrhiza uralensis*	P	15										5				65									30
	Lespedeza davurica	W	100	20	40	100	90	100	100	70	90	10	65	90			25	20				5		40	70	10
	Lespedeza floribunda	W																						5		
	Lespedeza cuneata	W											5	20												
	Robinia psendoacacia	W													10	5	10	30								
	Sophora viciifolia	W				40	20		60																	
	Astragalus scaberrimus	P			10	40	25	20																		
	Astragalus melitoloides	P		50	85	55	55	40	80	40	80	80	85	40												
	Oxytropis bicolor	P				20			20	50			25													
	Gueldenstaedtia verna	P				10																				
	Vicia sepium Linn	P												100												
Gramineae	*Melica scabrosa*	A																		10	30	50	45	10	30	50
	Roegneria kamoji	P				80	25				10			100												
	Calamagrostis epigeios	P			25																					
	Setaria viridis	A		40	25										100	100	100	65	80	100			10	10		
	Achnatherum splendens	P																75								
	Bothriochloa ischaemum	P		20	5	50	80	80				10														
	Leymus scalinus	P		10	25	15	25			100	90													50	10	5
	Phragmites communis	P							100												50	45	15			
	Koeleria cristata	P									10															
	Cleistogenes hancei	P								10																
	Cleistogenes squarrosa	P	75	40	65	85	65	10		20	60		15	20	45				10							

	Cleistogenes chinensis	P	65	30	40	40	80	75	50		10	100		20			25	15			20		5	10	10	60
	Poa sphondylodes	P	5								10		45	40												
	Poa annua	A																					30		20	5
	Stipa grandis	P	10							10	20															
	Stipa bungeana	P	90	100	70	75	80	65	100	100	100	80	55	40	75		10	95	45	90	100	85	90	90	100	80
Elaeagnaceae	*Hippophae rhamnoides*	W																								20
Violaceae	*Viola betonicifolia*	P								40	10		10	30												
	Viola dissecta	P	5							80	50	30	5	10	25	35		25	40	100	60	65	70	60	20	90
Compositae	*Saussurea japonica*	B														20	20		40		10			50		
	Heteropappus altaicus	P	85	100	85	45	55	75	10	70	60	70	75	50	55	50	50		35				5	10	10	5
	Bidens tripartita	A													75	100	100	65	60	20		15				
	Artemisia argyi	P																						80	80	10
	Artemisia hedinii	A												10	70	40	45	25	30							
	Artemisia giraldii	W				40	60	35	40			30	40	10				20						40	60	10
	Artemisia mongolica	P												30					50	20				30		
	Artemisia gmelinii	W	100	90	100	100	80	100	100	100	100	100	100	100				25	45	30				90	100	90
	Artemisia scoparia	A	30	90	70	55			20	10	30	10	30	60	15	50	100	15	30							
	Leontopodium leotopodioides	P									20		10													
	Circium segetum	P	75		15			15					10		20	65	45									
	Dendranthema indicum	P										10														
	Sonchus oleraceus	A			10										35	80	45			10	30	15	15		10	
	Ixeris denticulata	A	30	10	25	25	20	20	10			5	30				30	20	10							
	Serratula centauroides	P								20	20	10														
	Ixeris sonchifolia	P	35							60	20	10	85	20	10	10	10	50								
	Scorzonera divaricata	P						20																		
	Scorzonera sinensis	P						5																		
	Scorzonera austriaca	P								5																
Simarubaceae	*Ailanthus altissima*	T																	15					10		
Chenopodiaceae	*Salsola ruthenica*	A													85	90	75	15	40						50	20
Orobanchaceae	*Orobanche coerulescens*	A																					5			
Gentianaceae	*Swertia bimaculata*	A		60	45	50	20						15								50	10	25			
Asclepiadaceae	*Periploca sepium*	W																50		40	70	20	30			

	Cynanchum the-sioides	P																		70	40		25		20	10
	Cynancham chinense	P																	35	20			5			
Geraniaceae	*Erudium stephanianum*	P								30					10	10	10									
Ranunculaceae	*Pulsatilla chinensis*	P										60														
	Clematis fruticosa	W	10	20		20		20	10				15											20	20	30
Vitaceae	*Ampelopsis glandulosa*	W																				20				
Rubiaceae	*Rubia cordifolia*	P								10			10	20				30	65	60	10	60	25	90	20	40
Rosaceae	*Potentilla bifurca*	P				20	25			20	10			10												30
	Potentilla tanacetifolia	P	15			50					60	90		30												
	Rubus parvifolius	W																					10	50	60	30
Solanaceae	*Solanum nigrum*	A																	25			95	95			
Umbellifereae	*Bupleurum yinchowense*	P																						50		
Cyperaceae	*Carex lanceolata*	W																						50		
Scrophulariaceae	*Rehmannia glutinosoa*	P															15									
	Siphonostegia Chinense	A							10	10			10													
Convolvulaceae	*Convolvulus arvensis*	P													35		15	55		40		20				
Linaceae	*Linum usitatissimum*	A		30	30					20	30			10												
Ulmaceae	*Ulmus pumila*	W																					5			
Polygalaceae	*Polygala tenuifoli*	P				30	15		40			20	35	10												