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Modeling light availability for crop strips planted within apple orchard

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ABSTRACT

Rational design and management of the crop strips structure within fruit orchards are essential to make use of the economic and ecological advantages of intercropping but avoid the negative effects of resource competition on the fruit production. A better understanding of the light transmission processes could provide basis for quantifying resource competition and growth dynamics in the agroforestry system. Modeling work was combined with field experiment in this study to investigate light transmission in an apple tree (*Malus pumila* M.) and cocksfoot (*Dactylis glomerata* L.) intercropping system. The experiment was conducted in 2016 and 2017 in a plantation of apple at a spacing of 4 m × 4 m on the Loess Plateau of China. Three floor managing patterns were applied: clean tillage (CT), 2.4-meter-wide cocksfoot strips set up between tree rows that harvested more frequently to maintain a low coverage (LC), and cocksfoot strips with a greater coverage (GC). The light model simulates light transmission in the tree crown with a geometrical model that considering the canopy spatial heterogeneity, and describes light extinction in the crop strips with a strip-path radiation transmission model which is suitable for strip-path canopy structures. Results showed that the model well predicted fraction of incident light over and transmitted through the cocksfoot strips with determination coefficient of 0.707 and 0.892 respectively and root mean square error of 0.096 and 0.037. Averaged over the two seasons, light interception by cocksfoot were 439.1 and 504.7 MJ m^{-2} in LC and GC respectively, accounted for 23.1% and 26.5% of the total incoming light. Light use efficiency of cocksfoot in LC was far greater than that in the GC in both seasons. Planting cocksfoot showed no significant adverse effects on apple production, 6.32 and 5.67 t ha^{-1} additional dry forage were produced in the LC and GC plots respectively in 2016, the production were only 3.02 and 2.07 t ha^{-1} in 2017 as limited by water availability. Simulations with information on apple tree orchards of different age showed that seasonal mean fraction of light interception by cocksfoot under 3–10 years old apple trees varied from 0.41 to 0.29 for GC and from 0.36 to 0.25 for LC treatments, but the fraction became < 0.15 for 15 years and older orchards. This study provides basics for quantifying light and other resource competition in tree and crop intercropping systems and gives insights into floor management for rain-fed apple orchards on the Loess Plateau area of China.

1. Introduction

The Loess Plateau is one of the two largest apple producing areas in China. The traditional apple orchard floor management of intensive soil cultivation such as deep plowing and intertillage has exacerbated soil erosion and degradation (Liu et al., 2013; Ling et al., 2017). At the same time, rapid population growth has also brought greater pressure on food production in the region. The local government is facing dual pressures from both economy and ecology (Gao et al., 2011). Agroforestry is a potential way for solving the problem as it had been proven to have many ecological and economic advantages under different climatic conditions (Celette and Gary, 2013; Loewe et al., 2013; Uliarte et al., 2013; Meyer et al., 2015). Therefore, agroforestry management has been advocated by the local government to reduce soil erosion and water loss, raise land utilization rate and increase economic benefits in fruit production, and the pattern has been applied in some area (Fig. 1). However, a recent questionnaire survey on apple production on the Loess Plateau showed that the most popular floor management was still clean tillage and the number of households applying agroforestry was only accounted for 23.8%. Apprehension over water competition was the main reason that had limited the introduction of this floor management strategy (Wang et al., 2017a).

Although water is limited and yearly precipitation is variable in semi-arid environments, planting additional crops in orchards is not

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Fig. 1. The application of apple tree based agroforestry on the semi-arid Loess Plateau of China. (A) Apple tree and soybean (*Glycine* max L.) agroforestry, photo was cited from Gao et al. (2013a); (B) Apple tree and cocksfoot agroforestry, photo was taken by Zikui Wang.

always detrimental. The study of Du et al. (2015) showed that intercropping milk vetch (*Astragalus adsurgens* Pall.) in apricot (*Prunus armeniaca* L.) orchard reduced soil moisture and nutrients and Fang et al. (2016) also showed intercropping grasses reduced soil moisture in an apple orchard, however, the study of Bai et al. (2016) demonstrated the positive effect of planting grain crops on soil water conditions in an apricot orchard. In fact, the water competition between crop and fruit tree is affected by many factors such as crop species, intercropping canopy structure and rainfall distribution, and it could be alleviated by appropriate designing and managing the system. For example, yield performance and interspecific competition for resource in a jujube (*Zizyphus jujuba* Mill.) and cotton (*Gossypium hirsutum* L.) agroforestry system was strongly influenced by cotton density (Zhang et al., 2014) and the distance between tree row and cotton strip (Wang et al., 2017b). Water use and interspecific water competition was greatly reduced by mowing cover crops in a 2-year-old Sangiovese (*Vitis vinifera* L.) vineyard (Centinari et al., 2013). Canopy structure, the easiest managing factor, determines light transmission and partitioning in the intercropping, and light further influences other ecological and physiological processes in the system (Leroy et al., 2009). Thus, a good understanding of the light transmission processes is essential for quantifying resource use and optimizing the system. However, there have been few studies discussing the light availability for crops in fruit orchard, especially for the strip-planted crops that are commonly applied in arid and semi-arid environments.

Comprehensive and continuous measurement of light availability in an agroforestry is difficult because of the spatially heterogeneous canopy. Therefore, light extinction model is a useful tool for describing light transmission in complex canopies. If the canopy structure of an intercropping system is in several distinct layers, the amount of light interception by each layer could be calculated with the Beer's law (Keating and Carberry, 1993; Awal et al., 2006). This way is valid for agroforestry with full covered tree canopy and homogeneously distributed understorey canopy, but for systems with widely spaced tree canopy and/or strip-planted crops, it may result in large errors. Zhang et al. (2008) proposed that the intercropping canopy could be described by strip-path geometry and used the strip-path light transmission model (Goudriaan, 1977; Pronk et al., 2003) to estimate daily light interception. This modeling approach was applied by Zhang et al. (2014) to quantify the light utilization in an agroforestry of young jujube tree and cotton and by Gou et al. (2017) to estimate light partitioning in a wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.) strip intercropping. The assumption of strip-path structure could also be applied to simulate light transmission in the understorey crop strips in orchards, but it is not suitable for large and decentralized tree crowns. Geometrical radiation transmission model is based on geometrical relationships between beam direction and canopy architecture, which provides a practical basis for modeling light transmission in heterogeneous canopies. The geometrical approach was used for example by Tsubo and Walker (2002) to estimate the instantaneous light interception by a row-intercrop of bean and maize, by Munz et al. (2014a) to calculate light availability for the subordinate crop within a strip-intercrop of maize and bush bean (*Phaseolus vulgaris* L.), and by Wang et al. (2017c) to quantify border row effect on light interception in a wheat and maize intercropping. Further, this way was also applied in describing light transmission through tree crown (Charlesedwards and Thorpe, 1976; Palmer and Jackson, 1977; Norman and Welles, 1983), but light extinction in the understorey crop canopy was rarely considered in the geometrical model.

Therefore, the objectives of this study were to develop a light transmission model to simulate light interception and partitioning in the fruit tree and strip planted crop intercropping system, then quantify the temporal and spatial light availability for cocksfoot strips planted within an apple orchard under a semi-arid environment, investigate the effects of cutting management on light interception and use efficiency by cocksfoot, and finally simulate the effects of canopy structure on light partitioning within this intercropping system.

2. Material and methods

2.1. Light transmission model

The variables used as model input and calculated in the model are listed in Table 1. The procedure provided by Christopher (2006) was used to calculate the solar declination (δ) for a given day, and local solar time (t_s), solar azimuth form south (α), solar elevation (β), and extraterrestrial solar radiation (R_a) for any given time in the day. The set of equations proposed by de Jong (1980) for hourly solar radiation partitioning and its correction by Spitters et al. (1986) for photosynthetically active radiation (PAR) was applied in this work to partition the incident PAR into direct and diffuse fractions. For seasonal simulation, the incident PAR was estimated from measured solar radiation with the method provided by Tsubo et al. (2005):

$$\mathrm{PAR} = R_s(0.150K_T^2 - 0.401K_T + 0.635) \quad (1)$$

where R_s is solar radiation, and K_T is the ratio of global to extraterrestrial solar radiation. This equation reflects the effects of cloudiness on PAR fraction. The calculated onsite PAR/R_s is approximately 0.42 on completely sunny days and > 0.60 under very cloudy skies.

For a given beam, we calculated the fraction of light available on the level of the crop canopy surface firstly, and then the fraction transmitted onto the soil surface (Fig. 2A). A direct beam transmission through the tree canopy onto the crop surface level can be simulated by the Beer's law (Monsi and Saeki, 1953; Tsubo and Walker, 2002):

Table 1
Definition and units of variables used as model inputs and of variables calculated in the model.

Variable	Definition	Units
Model input		
γ	Longitude	degrees
ε	Absorption coefficient of leaves	–
λ	Latitude	Degrees
χ	Ratio of vertical to horizontal projections of canopy element	–
g	G function light extinction coefficient for apple tree	–
h_c	Height of crop strip	m
h_t	Height of tree canopy	m
k	K function light extinction coefficient of understorey crop	–
LAI_c	Leaf area index of understorey crop	$m^2 m^{-2}$
LAI_t	Leaf area index of apple tree	$m^2 m^{-2}$
p	Canopy reflection coefficient	–
R_s	Global solar radiation	$MJ m^{-2} day^{-1}$
r_x, r_y, r_z	Width, length and height of ellipsoid semi-axes of the tree canopy	m
t_d	Difference between local and solar time	Hour
t_l	local time	Hour
w_p	Width of bare path between crop strips	m
w_s	Width of crop strip	m
Model calculation		
α	Solar azimuth from south	Degrees
β	Solar elevation	Degrees
δ	Solar declination	Degrees
d	Light transmission distance in the tree canopy	m
f_c	Fraction of radiation intercepted by crop strip	–
f_{csl}	Fraction of incident radiation on the level of crop canopy surface	–
f_{csl_dPAR}	Diffuse fraction of incident PAR on cocksfoot strip surface level	–
f_{csl_DPAR}	Direct fraction of incident PAR on cocksfoot strip surface level	–
f_{ip}	Fraction of incident radiation on the top of the path	–
f_{ip_dPAR}	Diffuse fraction of incident PAR on the top of bare path	–
f_{ip_DPAR}	Direct fraction of incident PAR on the top of bare path	–
f_{is}	Fraction of incident radiation on the top of the crop strip	–
f_{is_dPAR}	Diffuse fraction of incident PAR on the top of cocksfoot strip	–
f_{is_DPAR}	Direct fraction of incident PAR on the top of cocksfoot strip	–
f_{PAR}	Fraction of PAR intercepted or transmitted	–
f_{PAR_daily}	Daily fraction of PAR interception	–
$f_{PAR\_seasonal}$	Seasonal fraction of PAR interception	–
f_s	Fraction of incident radiation on soil surface	–
f_{ss}	Fractions of radiation transmitted onto the soil surface beneath the crop strip	–
f_{sp}	Fractions of incident radiation on soil surface of the path	–
f_t	Fraction of radiation intercepted by the tree canopy	–
I_{is}	Incident PAR over understorey crop strip	$\mu mol m^{-2} s^{-1}$
I_{ss}	Incident light beneath crop strip	$\mu mol m^{-2} s^{-1}$
K_T	Ratio of global to extraterrestrial solar radiation	–
LAD	Leaf area density	$m^2 m^{-3}$
PAR	Photosynthetically active radiation	$\mu mol m^{-2} s^{-1}$
R_a	Extraterrestrial solar radiation	$MJ m^{-2} day^{-1}$
r_{ia}	Radius of influencing area for a given tree in light transmission modeling	m
t_s	Solar time	Hour

$$f_{csl} = (1 - p)\exp\left(-\sum_{i=1}^{n}\sqrt{\varepsilon}gLADd_i\right) \tag{2}$$

where f_{csl} is the fraction of radiation available on the level of crop strip surface, p is the canopy reflection coefficient and the value for PAR is approximately 0.04 as calculated by Goudriaan and van Laar (1994); ε is the absorption coefficient of leaves and a value of 0.80 is usually applied for PAR (Christopher, 2006); g is the canopy extinction coefficient (the average projection area of canopy elements onto a surface

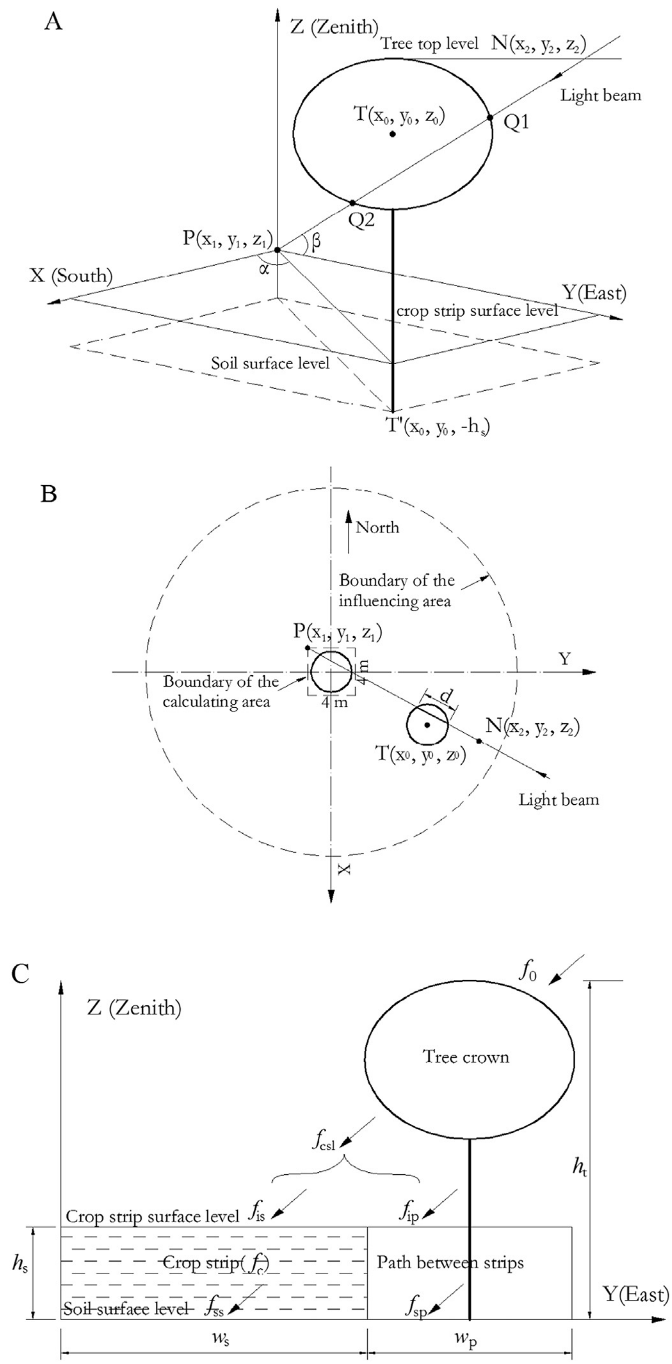

Fig. 2. Diagram of the beam transmission in the tree and cover crop intercropping canopy. Fig. A shows the Cartesian and angular coordinates, the canopy envelope of the tree is taken as the geometrical shape of an ellipsoid with the center of T, Q_1 and Q_2 are the points where the beam enters and exits the tree canopy, P is the point on the level of cover crop surface where the beam reaches, N is the intersection point of light beam and the level of tree canopy top, and α and β are beam azimuth and elevation respectively. Fig. B defines the area of the trees influencing the incident light within the area under the target tree. Fig. C shows a front view of the tree-crop-path system and radiation partitioning processes, f_0, f_{csl}, f_{is}, f_{ip}, f_{ss} and f_{sp} present fraction of incident light on the tree crown, crop strip surface level, strip top, path top, strip bottom and path bottom respectively.

normal to the direction of the projection); LAD ($m^2\,m^{-3}$) is the leaf area density of apple tree; d_i (m) is the light transmission distance in the ith tree canopy.

The canopy extinction coefficient g is calculated with the G function (Campbell and Norman, 1989):

$$g = \frac{\sqrt{\chi^2 \sin^2\beta + \cos^2\beta}}{\chi + 1.774(\chi + 1.182)^{-0.773}} \tag{3}$$

where χ is the ratio of vertical to horizontal projections of canopy element, a value of 1.0 was applied in this study, which means that the leaf angle of apple tree is spherically distributed. Several studies have showed that the assumption of leaf spherical distribution was feasible for radiation simulation in tree crops (Campbell and Norman, 1989; Christopher, 2006; Gong et al., 2006).

The tree crown is taken as an ellipsoid in this work to simplify calculations and it is assumed that all of small leaves are randomly distributed with a constant probability throughout the volume defined above. The LAD is then calculated as:

$$LAD = \frac{16LAI_t}{{}^4\!/_3\pi r_x r_y r_z} \tag{4}$$

where LAI_t is the leaf area index of apple tree, the coefficient 16 (m^2) represents the land area occupied by a single tree, and r_x, r_y and r_z (m) are the width, length and height of ellipsoid semi-axes of the tree canopy, respectively.

The area occupied by a certain tree (4 m × 4 m) was set as our light simulating area (Fig. 2B). The calculating intervals of PAR is set to be 0.20 m, so light incident on 441 points at crop strip surface level (21*21 with horizontal and longitudinal adjacent distances of 0.20 m) was simulated. Both direct and diffuse light transmitted to a certain point is affected by one or more trees around it. We defined an influencing area and suppose that all of the trees within it affecting the incidence light under the target tree, and radius of influencing area, r_{ia}, was estimated as:

$$r_{ia} = {h_{t\max}}/{\tan\beta_0} \tag{5}$$

in which β_0 is the solar elevation at 5.5 h before or after solar noon and h_{tmax} is the maximum height of tree canopy. Averaging over the apple tree growing season, solar radiation within 11 h around the solar noon accounts for 97.1% of the daily total solar radiation. The radius in this study was estimated as 19.6 m, 73 trees in total were included in this area. For each light beam, its transmission distances in the 73 trees were calculated and summed up to get the total transmission distance.

To calculate light transmission distance in a single tree, Cartesian and angular coordinates were built to describe the geometrical relationship between light beam and plant canopies (Norman and Welles, 1983), as shown in Fig. 2A. The canopy envelope of the apple tree is taken as the geometrical shape of an ellipsoid. Q_1 and Q_2 are the points where the light beam enters and exits the tree canopy, $P(x_1, y_1, z_1)$ is the point on the level of crop surface where the beam reaches, and $N(x_2, y_2, z_2)$ is the intersection point of light beam and the level of tree canopy top. The beam is attenuated according to the leaf-area index projected on to the plane normal to the path Q_1Q_2. Suppose that the center of the tree canopy surface is $T(x_0, y_0, z_0)$, then the tree canopy can be described by the equation:

$$((x - x_0)/r_x)^2 + ((y - y_0)/r_y)^2 + ((z - z_0)/r_z)^2 = 1 \tag{6}$$

Suppose that the distance from P to Q is t, then the coordinates of Q_1 and Q_2 satisfy the equations:

$$(x - x_1)/\cos\beta\cos\alpha = (y - y_1)/\cos\beta\sin\alpha = (z - z_1)/\sin\beta = t \tag{7}$$

Using Eq. (7), x, y and z can now be eliminated from Eq. (6), giving a quadratic of the form:

$$At^2 + Bt + C = 0 \tag{8}$$

where the coefficients A, B, and C are expressed as:

$$A = {r_z}^2\cos^2\beta + {r_x}^2\sin^2\beta \tag{9a}$$

$$B = 2{r_z}^2(x_1 - x_0)\cos\alpha\cos\beta + 2{r_z}^2(y_1 - y_0)\sin\alpha\cos\beta + 2{r_z}^2(z_1 - z_0)\sin\beta \tag{9b}$$

$$C = {r_z}^2(x_1 - x_0)^2 + {r_z}^2(y_1 - y_0)^2 + {r_z}^2(z_1 - z_0)^2 - {r_x}^2{r_z}^2 \tag{9c}$$

From Eq. (8) we know that difference of the two t values, namely, the path length of radiation within the tree canopy, can be calculated as:

$$d = \begin{cases} \sqrt{B^2 - 4AC}\,/|A| & B^2 - 4AC > 0 \\ 0 & B^2 - 4AC \le 0 \end{cases} \tag{10}$$

The transmission of diffuse radiation can be derived by integrating the direct radiation attenuation function over the hemisphere (all zenith and azimuth angles) after assuming that the diffuse radiation originates from all sky angles. In the present study, the diffuse radiation was approximated using an array of 324 directional light sources positioned regularly in a hemisphere in 6 circles (elevation of 7.5°, 22.5°, 37.5°, 52.5°, 67.5°, and 82.5°) with 12 light sources (30° in azimuth between adjacent sources) each.

Fraction of radiation intercepted by the tree canopy, f_t, is calculated as:

$$f_t = 1 - f_{csl} \tag{11}$$

Canopy below the crop surface level could be deemed as a strip-path structure (Fig. 2C). If we have relatively narrow and short crop strip, and the path width is far greater than the strip height, there would be a weak interaction between the strip and path in light transmission. The fraction of radiation intercepted by crop strip, f_c, and incident on soil, f_s, could be calculated directly with the Beer's law:

$$f_c = f_{is}(1 - e^{-kLAI_c}) \tag{12}$$

$$f_s = f_{ip} + f_{is}e^{-kLAI_c} \tag{13}$$

where f_{is} and f_{ip} are the fraction of incident radiation on the top of the crop strip and path, calculated from f_{csl} and the proportion of field taken by crop strip and path. LAI_c is the leaf area index of the crop and k refers to the light extinction coefficient of the crop. The k value for cocksfoot in this study was derived from incident PAR values measured above (I_{is}) and beneath (I_{ss}) the cocksfoot strip in 2016:

$$k = -\ln\left(\frac{I_{ss}}{I_{is}}\right)/LAI_c \tag{14}$$

If the height of crop strip is comparable or greater than the path width, crop strip would have a shading effect on the path and a part of incident light on top of the path would be intercepted by the nearby crop strip rather than totally transmit onto the bare path as assumed by the statistical model that considering light transmission in strip and path separately. So the original model would underestimate the radiation interception by crop strip. The strip-path radiation transmission model (Goudriaan, 1977; Zhang et al., 2008; Wang et al., 2015a) could be applied under this condition. In this model, the incident radiation on top of the bare path is divided into two portions, FP_{black} and 1- FP_{black}, the fraction FP_{black} transmits directly onto the path surface, while 1- FP_{black} is attenuated by a hypothesized horizontally homogeneous canopy onto the soil surface of the path and under the crop strip. The radiation incident on the crop strip transmits in the same way, except that the fraction FS_{black} is attenuated by crop leaves before reaching the soil surface. Thus, the fractions of incident radiation on the path, f_{sp}, beneath the crop strip, f_{ss}, and intercepted by crop strip, f_c, are as follows:

$$f_{sp} = f_{ip}\,[FP_{black} + f_{ip}\,(1 - FP_{black})\mathrm{e}^{-kLAI_c'}] + f_{is}f_{ip}\,[(1 - FS_{black})\mathrm{e}^{-kLAI_c'}] \tag{15}$$

$$f_{ss} = f_{is}\,[FS_{black}\mathrm{e}^{-kLAI_c} + f_{is}\,(1 - FS_{black})\mathrm{e}^{-kLAI_c'}] + f_{ip}f_{is}\,[(1 - FP_{black})\mathrm{e}^{-kLAI_c'}] \tag{16}$$

$$f_c = f_{csl} - f_{sp} - f_{ss} \tag{17}$$

where LAI_c' is leaf area index that calculated as the ratio of crop leaf area to the whole field. FP_{black} and FS_{black} are parameters related with structure of the crop strip:

$$FP_{black} = (\sqrt{h_c^2 + w_p^2} - h_c)/w_p \tag{18}$$

$$FS_{black} = (\sqrt{h_c^2 + w_s^2} - h_c)/w_s \tag{19}$$

where h_c is the canopy height of crop, w_p is the bare path width between the crop strips, and w_s is the strip width.

2.2. Field experiment

Field experiment was carried out during the growing season of 2016 and 2017 in an apple orchard at the Qingyang Experimental Station of Lanzhou University (40°54′N, 107°09′E, and altitude 1035 m), which is located in the central part of the Loess Plateau in China. The site is in a semiarid zone with mean annual temperature of 9.2 °C, mean annual precipitation of 527.6 mm, and average annual sunshine duration of 2415 h. Meteorological data (air temperature, relative humidity, wind speed at 2-m-height, solar irradiance and precipitation) were recorded half-hourly at the onsite agriculture meteorological station (Vantage Pro2, Davis Instruments, Hayward, CA, USA). Soil at the site is silty loam with the organic matter content of 5.72 and 3.77 g kg^{-1} in the 0–40 and 40–100 cm layers respectively at the time of cocksfoot sowing. Field capacity and wilting point were measured at different depths and the averaged values were 0.29 $\mathrm{m^3\,m^{-3}}$, and 0.11 $\mathrm{m^3\,m^{-3}}$ in the upper 200 cm of the soil profile.

The apple trees (*Malus pumila* M. cv Qingguan) were planted in north-south rows, 4.0 m within-row spacing and 4.0 m between the rows. Trees were 11 years old in 2016, with a trunk diameter between 150 and 190 mm. The tree crowns were between 3.0 and 3.6 m in height and width was between 3.2 and 4.1 m. Considering the uneven size of apple trees, we recorded the bottom trunk diameter distribution of the apple trees at the beginning of experiment. Three plots with an area of 480 m^2 (including six 20-meter-long tree rows) were built in the orchard to implement different floor management treatments and three representative apple trees were selected in each plot for the measurements of canopy dynamics and light conditions. The floor was treated as: (1) no cover crop with clean tillage (CT), (2) cover crop of cocksfoot (*Dactylis glomerata* L.) with a lower coverage (LC, cocksfoot was harvested 4–5 times during the apple tree growth season), and (3) cover crop of cocksfoot with a greater coverage (GC, cocksfoot was harvested 2–3 times). For the cover crop treatments, cocksfoot was sown between the tree rows in the July of 2014 with a strip width of 2.4 m. The distance from the strip border to the tree row is 0.8 m.

Leaf area index (LAI) of apple tree was measured using an LAI-2000 plant canopy analyzer (LI-COR Biosciences, Lincoln, NE, USA). Measurements under tree were made at the level about 5 cm above cocksfoot canopy and 10 measurements distributed over the $4 \times 4\,\mathrm{m}^2$ area under a certain tree were averaged to represent a replicate of LAI. A logistic equation was used to describe the relationship between LAI and days after bud burst (DAB):

$$LAI = \frac{a}{1 + b\mathrm{e}^{-cDAB}} \tag{20}$$

where a, b, and c are the fitted coefficients, a means the maximum LAI, b equals the ratio of the maximum to the initial LAI minus 1, and c means the daily increasing rate of LAI. This equation was also used to estimated LAI dynamics in different aged apple orchards. All of the apples on six trees in different treatments were collected and weighted, the yields of trees were averaged to get the final yield of each treatment.

Cocksfoot was sampled every 15–20 days with a quadrat of $1.0 \times 1.0\,\mathrm{m}^2$, fresh weight was determined first, and then 5 plants were subsampled to determine the LAI. The subsample was weighted and then the total leaf area was measured with a leaf area meter (AM200, ADC BioScientific Ltd., UK). LAI value for the cocksfoot stand was calculated as the area of the subsample times the ratio of the total fresh weight/subsample fresh weight divided by sampled ground area. The plant samples were finally dried to constant weight at 75 °C to give the dry matter production of cocksfoot. An ANOVA with floor treatment and year as main effects was conducted for apple and cocksfoot yield to determine the significance of the differences between treatments and years. For apple yield, the multiple comparison among the floor treatments within each season was conducted using Turkey's LSD at $P = .05$.

In both GC and LC treatments, the incident photosynthetically active radiation (PAR, 400–700 nm) on the level of cocksfoot canopy surface was measured manually with a linear AccuPAR LP-80 Ceptometer (Decagon Devices, Pullman, Washington, USA). PAR measurements were taken every 2 h from 8:00 to 18:00 on 11 dates in 2016 and 9 dates in 2017. Sky was clear on these dates. Light was measured at 16 positions, namely, four positions on each of the east-south-west-north direction with distances to the tree trunk of 0.5, 1.0, 1.5 and 2.0 m. To evaluate light transmission in the cocksfoot canopy, 10 pairs of PAR data above and beneath the cocksfoot strip were collected every 2 h from 9:00 to 17:00 on the same dates.

2.3. Model validation and simulation analysis

Model inputs are site position (latitude and longitude), date (day of year), local time, canopy configuration, solar radiation, and light absorption, reflection and extinction coefficients. Daily values of canopy height and LAI were derived by linear interpolation between measured values. Instantaneous PAR data measured at the level of the cocksfoot surface were used to validate light transmission simulation in apple tree canopy, and the data measured beneath the cocksfoot strip were used to validate light transmission equations in the cocksfoot canopy. Fractions of PAR (f_{PAR}) were used in the model validation. The statistical indices mean absolute error (MAE), root mean square error (RMSE), and determination coefficient (R^2) were used. These indices have the following expressions:

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N} |S_i - O_i| \tag{21}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (S_i - O_i)^2} \tag{22}$$

$$\mathrm{R}^2 = \frac{[\sum_{i=1}^{N}(O_i - \overline{O})(S_i - \overline{S})]^2}{\sum_{i=1}^{N}(O_i - \overline{O})\sum_{i=1}^{N}(S_i - \overline{S})} \tag{23}$$

where S_i and O_i are simulated and observed fraction of incident PAR respectively, $\overline{S}$ and $\overline{O}$ are mean of simulated and observed values respectively, and N is the number of instances in the dataset.

After model validation, diurnal dynamics of f_{PAR} available on the cocksfoot canopy surface level were evaluated on a typical sunny day. The seasonal dynamics of f_{PAR} available on the top of cocksfoot strips and bare path were also evaluated. For both experiment years, light portioning among apple tree, cocksfoot and soil were then calculated, light interception and light use efficiency by cocksfoot in different treatments were examined. The effect of apple tree canopy structure on cocksfoot light interception was finally investigated with canopy information of different aged apple orchards.

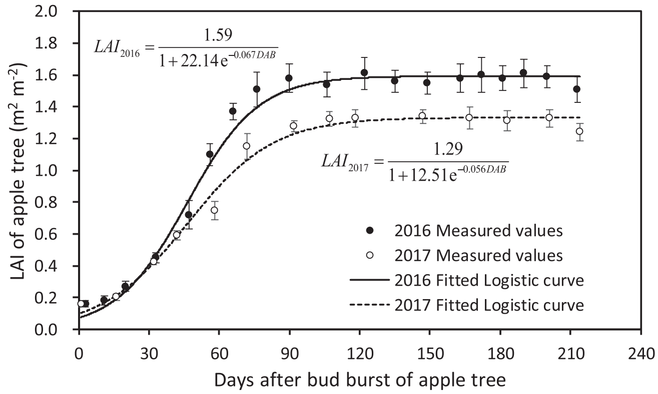

Fig. 3. Measured values and fitted Logistic curve for apple tree leaf area index.

3. Results

3.1. Canopy development and yield

Canopy analysis showed that the LAI values of apple tree in the three floor treatments were not significantly different from each other on most measuring dates, so the LAI data were pooled together to show the LAI dynamics of the apple tree in each of the year (Fig. 3). In the spring, buds start to burst and the LAI increased from 0.2 $m^2 m^{-2}$ to a maximum of about 1.59 $m^2 m^{-2}$ in 2016 and 1.29 $m^2 m^{-2}$ in 2017 at approximately 3 months after budding. After that, the LAI maintained a relatively steady value toward the end of the season. Apple was harvested in the late October, when most of the leaves were still green, so no apparent decreasing trend in LAI was found during the late season. Limited rainfall in the spring of 2017 constrained the canopy development of apple tree.

Fig. 4 shows the LAI dynamics of cocksfoot within the orchard in the two seasons, the values were set as the ratio of total leaf area to land area occupied by cocksfoot strip. The leaf of cocksfoot expanded quickly during the early growth after each harvest, and the expansion rate slowed down after about 30–40 days after cutting. The overall growth rate in 2016 were greater than that in 2017. The maximum LAI in LC and GC were 5.8 and 7.3 $m^2 m^{-2}$ respectively in 2016, 4.5 and 5.8 $m^2 m^{-2}$ in 2017. More frequent harvest significantly reduced the coverage of the orchard floor. Seasonal average LAI in the LC and GC treatments were 2.8 and 4.3 $m^2 m^{-2}$ respectively in 2016, and were 2.4 and 3.7 $m^2 m^{-2}$ in 2017. There were 146 days on which LAI of GC was greater than that of LC treatment in 2016, and in 2017 there were 135 days.

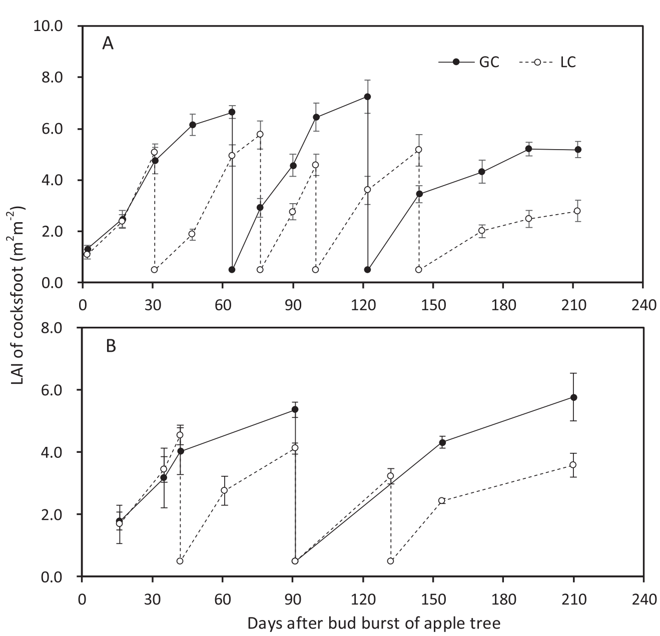

Fig. 4. Leaf area index dynamics for cocksfoot planted within the apple orchard during the apple tree growing season in 2016 (A) and 2017 (B).

Table 2 presents the fresh fruit yield of apple and aboveground dry matter yield of cocksfoot in both seasons. Averaging over different floor management treatments, the final fresh fruit yield of the apple in 2016 was significantly greater than that in 2017 ($P = 0.003$), but no significant differences were found among different treatments in both years ($P = 0.985$). Cocksfoot dry matter of the five cuttings in LC plots were 1.33, 1.62, 0.90, 1.31, and 1.17, respectively, with the total dry matter of 6.32 t ha^{-1}, and that of the three cuttings in GC plots were 2.36, 2.09, and 1.23 t ha^{-1}, respectively, with the total dry matter of 5.67 t ha^{-1} in 2016 (Table 2); and in 2017, the dry matter of the four cuttings in LC treatment were 0.95, 0.82, 0.59, and 0.66, respectively, with the total dry matter of 3.02 t ha^{-1}, and that of the two cuttings in GC treatment were 0.57 and 1.50 t ha^{-1} respectively, with the total dry matter of 2.07 t ha^{-1} (Table 2). More dry matter was therefore produced in the LC plots in both years ($P < 0.001$).

3.2. Validation of light transmission model

PAR data measured at the level of the cocksfoot surface were used to validate light transmission through the apple tree canopy. A comparison of simulated fraction of PAR against the measured values is shown in Fig. 5. We can see that the model showed satisfactory performance in both years, with all points distributed along both sides of the 1:1 line. Fraction of incident PAR on the cocksfoot strip surface level (f_{csl}) ranged between 0.2 and 0.8 in both years but more large values occurred in 2017 because the coverage of apple tree was lower. Statistical results showed that in 2016, the determination coefficient of regression was 0.584, and the root mean square error (RMSE) and mean absolute error (MAE) of the simulated f_{csl} were 0.077 and 0.090 respectively, and in 2017 the determination coefficient of regression was 0.829, and the RMSE and MAE of the simulated f_{csl} were 0.081 and 0.101 respectively.

PAR values measured above and beneath the cocksfoot strip in 2016 were used to derive light extinction coefficient k of cocksfoot and those measured in 2017 were used to validate light transmission equations in the cocksfoot canopy. Regression showed that there is a significant linear correlation between natural logarithm of radiation transmission and the LAI of cocksfoot (slope = -0.441, $R^2 = 0.95$). The light extinction coefficient is thus 0.441. As for other forage grasses, the k value of cocksfoot was weakly affected by the LAI value and time of the day (Kiniry et al., 2011). Comparison of simulated fraction of PAR transmitted onto soil beneath cocksfoot strip (f_{ss}) against the measured values is also shown in Fig. 5. We can see that the overall tendency of the simulated f_{ss} harmonized with the measured values. The determination coefficient of regression was 0.892 and the MAE and RMSE of the simulation were 0.030 and 0.037 respectively.

3.3. Temporal and spatial variability of light incident on cocksfoot

Diurnal variation in fraction of instantaneous PAR incident on the cocksfoot strip surface level for a typical sunny day (Sep 27th in 2016, DAB 181, $LAI_t = 1.58$) was showed in Fig. 6. The diffuse light was supposed to be isotropic and only influenced by canopy structure and LAI of tree, so the diffuse fraction of PAR (f_{csl_dPAR}) maintained a stable value throughout the day. The diffuse fraction on top of the path (f_{ip_dPAR}) was much lower than that on the crop strip (f_{is_dPAR}). The direct fraction (f_{csl_DPAR}) changed over the day as the solar incident angle varied, it had relatively low values in the early morning and late afternoon and reached the maximum values at solar noon (local time of 12:49). The direct fraction on top of the path (f_{ip_DPAR}) had a bimodality

Table 2
Fresh fruit yield of apple and aboveground dry matter yield of cocksfoot and the *P* values of ANOVA for year, treatment and year × treatment effects. The yield of cocksfoot was calculated based on the land area occupied by both strip and path.

Year	Treatment	Apple yield	Cocksfoot yield ($t\,ha^{-1}$)					
		($t\,ha^{-1}$)	1st cutting	2nd cutting	3rd cutting	4th cutting	5th cutting	Total
2016	LC	57.3	1.33	1.62	0.90	1.31	1.17	6.32
	GC	57.7	2.36	2.09	1.23			5.67
	CT	59.3						
2017	LC	45.5	0.95	0.82	0.59	0.66		3.02
	GC	45.1	0.57	1.50				2.07
	CT	45.0						
Year		0.003						< 0.001
Treatment		0.985						< 0.001
Year × treatment		0.987						0.170

pattern with the maximum values at around 3 h before and after solar noon, and that incident on cocksfoot strip (f_{is_DPAR}) had the greatest value at solar noon.

Seasonal dynamics of daily fraction of direct incident PAR on the top of cocksfoot strip and bare path, f_{is_DPAR} and f_{ip_DPAR}, are show in Fig. 7A. It can be seen that fraction of direct light on cocksfoot strip and bare path were almost the same before 110 DAB, and the difference appeared and became larger thereafter. This is because solar elevation angle decreases during the late season and the northern shadow of the tree crown was longer and longer, bare strip under the crown was largely affected. The seasonal dynamics diffuse PAR, denoted as f_{is_dPAR} and f_{ip_dPAR}, are show in Fig. 7B, which has an opposite tendency with the tree LAI. Less diffuse light was transmitted onto the bare path and the difference between the cocksfoot strip and path became lager as tree LAI increased. Averaged over the two seasons, fractions of direct PAR on the cocksfoot strip and bare path were both 69.0% before 90 DAB of apple tree, and the fractions were 51.7 and 42.7% respectively during the remaining season. For diffuse PAR, the fractions were 61.7 and 57.0% before 90 DAB of apple tree, and were 44.8 and 37.1% during the remaining season.

Both diffuse and direct light incident on the cocksfoot surface level was averaged over both the season and the north-south direction to present the light distribution on the west-east direction (cross-row direction), as shown in Fig. 8. Both direct and diffuse light were symmetrically distributed along both sides of the tree trunk. The diffuse light was linearly increased from tree trunk to the inter-row and the averaged fraction of light incident on the cocksfoot strip was 12.7% greater than that on the bare path over two seasons. Direct light decreased from the tree trunk to the border of bare path and then increased, light in the central 0.8-m cocksfoot strip was the greatest. The averaged fraction of direct PAR incident on the cocksfoot strip was only 4.1% greater than that on the bare strip.

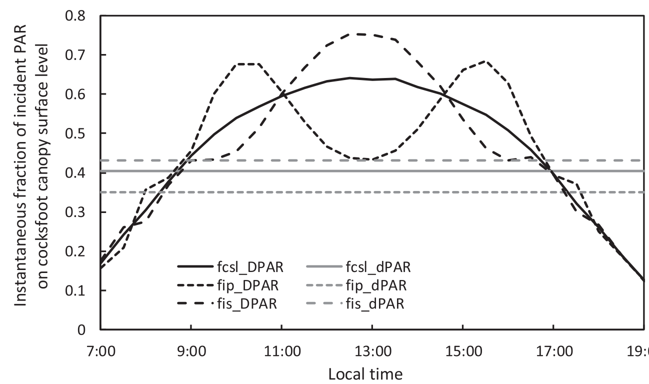

Fig. 6. Diurnal variation in fraction of instantaneous incident PAR on the cocksfoot canopy surface level on a typical sunny day (Sep 27th in 2016, DAB 181, LAI_t = 1.58).

3.4. Light interception and use efficiency

Seasonal courses for the daily fraction of PAR interception (f_{PAR_daily}) by apple tree, cocksfoot and soil are depicted in Fig. 9. During the first 60 days, the f_{PAR_daily} of apple tree increased quickly as its leaf area expanded, and then it increased gradually until the end of the season, which is different with the tendency of the LAI. The f_{PAR_daily} of the cocksfoot and soil showed opposite tendency, but the fraction of soil was greater than that of the cocksfoot on most days, especially in 2017 when the cocksfoot had a relatively low coverage. The difference between cocksfoot cutting treatments was also clearly showed in the figure for both years, the GC treatment maintained greater light interception values on most days throughout the season.

Throughout the whole growing season, total PAR interception by apple tree were 930.3 and 787.7 $MJ\,m^{-2}$ in 2016 and 2017

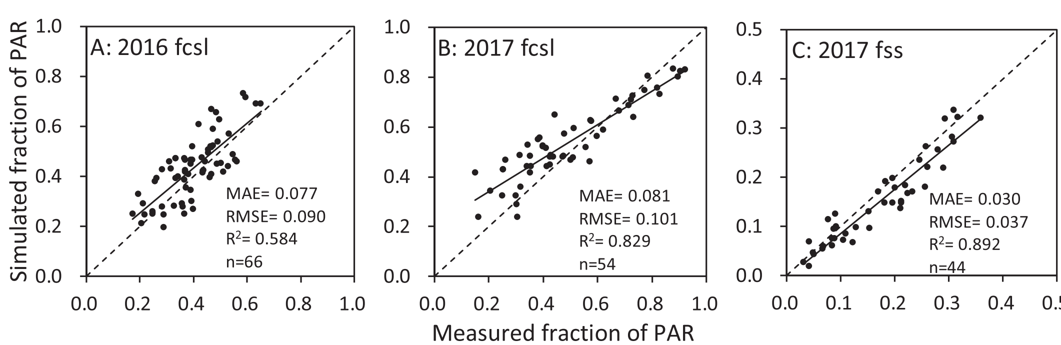

Fig. 5. Comparison of simulated fraction of PAR against the measured values, solid lines are regression fits and dashed lines show 1:1 relationship. (A) Fraction of incident PAR on the cocksfoot strip surface level in 2016, (B) fraction of incident PAR on the cocksfoot strip surface level in 2017 and (C) fraction of incident PAR on the soil beneath cocksfoot strip.

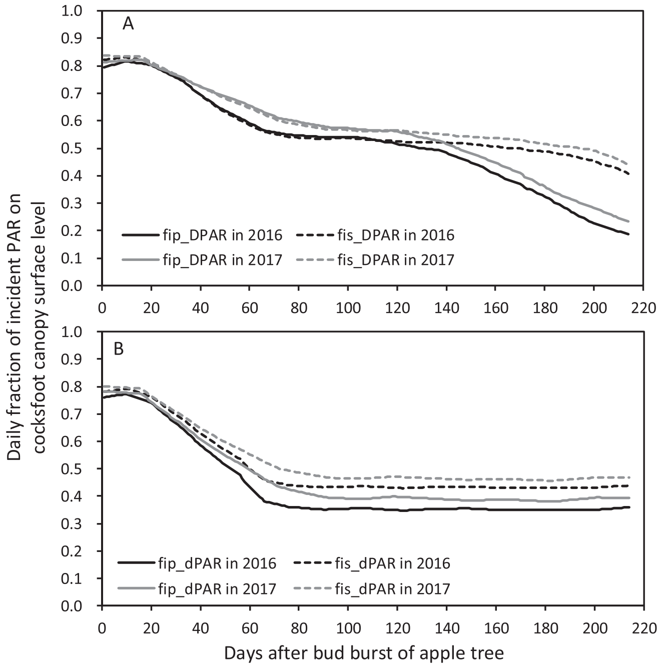

Fig. 7. Seasonal dynamics of daily fraction of direct (A) and diffuse (B) incident PAR on the top of cocksfoot strip and bare path.

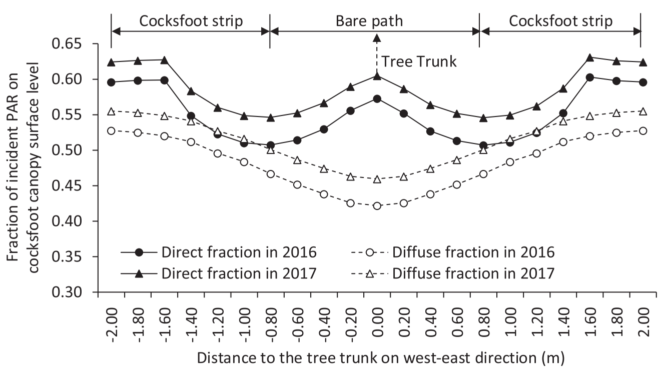

Fig. 8. Spatial distribution of direct and diffuse PAR on the cocksfoot strip surface level.

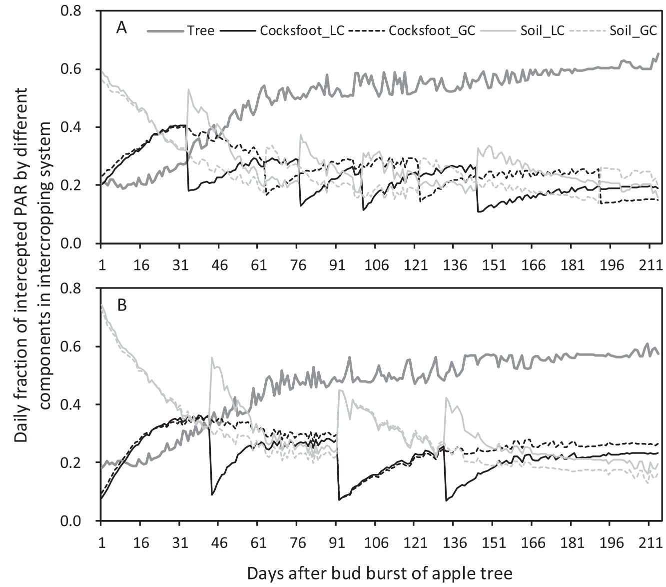

Fig. 9. Seasonal courses of daily fraction of PAR interception by apple tree, cocksfoot and soil in the apple tree and cocksfoot intercropping in 2016 (A) and 2017 (B).

respectively, and those values for cocksfoot were 465.3 and 412.9 MJ m^{-2} in the LC treatment and 535.1 and 474.3 MJ m^{-2} in the GC treatment. Averaged over the two seasons, the seasonal fraction of light interception ($f_{PAR\_seasonal}$) by cocksfoot were 23.1% and 26.5% in LC and GC respectively. Light use efficiency of cocksfoot were 1.36 and 1.06 g MJ^{-1} in the LC and GC treatments respectively in 2016, and were 0.73 and 0.47 g MJ^{-1} in 2017.

3.5. *Effects of canopy structure on cocksfoot light interception*

Canopy parameters of apple trees of different ages were derived from another study also conducted in rain-fed orchards on the Loess Plateau (Wang et al., 2010), which are listed in Table 3. The trees in different orchards are all planted with an inter-row distance of 5.0 m and an intra-row distance of 4.0 m, and the tree crown structure is very similar with that in our experiment. The temporal dynamics of LAI for those orchards were also described with logistic curves, since the maximum values of LAI were known and the initial values were supposed to be 0.15 for all ages of trees, and the growth stages were set to be the same as in our study.

LAI data of cocksfoot in 2016 were used to evaluate the effects of tree canopy size on light interception. Dynamics of cocksfoot f_{PAR_daily} in LC treatment is shown in Fig. 10A. We can see that for early aged orchard, the f_{PAR_daily} hold a large and relatively steady value throughout the season, but a decreasing tendency of f_{PAR_daily} through the season was found for orchards equal or older than 10 years, which became more pronounced with increasing tree age. $f_{PAR\_seasonal}$ of cocksfoot under 3–10 years old apple trees varied from 0.41 to 0.29 for GC and from 0.36 to 0.25 for LC treatments. A drastic decrease was found from 10 to 15 years old orchards, and the $f_{PAR\_seasonal}$ was < 0.15 for 15 years and older orchards.

Light transmission in the understorey is mainly influenced by the LAI, strip height and strip width of cocksfoot. Strip width is directly affecting light interception and resource uptake by cocksfoot strips. As shown in Fig. 8, light availability on the level of cocksfoot strip surface had a weak variation through the cross-row direction, the $f_{PAR\_seasonal}$ of cocksfoot strips was almost linearly related with strip width for all of the orchards (Fig. 10B). The height of cocksfoot affects light partitioning between crop and soil. From Fig. 10C we see that the model without considering strip height underestimated light interception by the cocksfoot strip and the under-estimation increased as the strip height increased. But the underestimation was only 4.53% for LC treatment in 2016 since the strip height was controlled below 50 cm (data not shown).

4. Discussion

Forest canopies are often not homogeneous, and may contain multiple horizontal layers or canopy gaps (Macfarlane et al., 2007). Statistical modeling approaches used to simulate radiation extinction in homogeneous canopies, with leaves randomly distributed in space, are not applicable for discontinuous canopies because it would overestimate light interception of the canopy (De Melo-Abreu et al., 2002; Wang et al., 2015a). The accuracy of light models usually increases with the level of detail used to describe the tree crowns and canopy structure. However, complex models require too many input parameters and a high computational effort making them unattractive for use in growth models designed to be easy to parameterize and quick to run at large temporal and spatial scales (Forrester and Albrecht, 2014). The model developed in this study considered the heterogeneity of tree canopy but simplified the crown structure and leaf distribution based

Table 3
Canopy information of different aged apple orchards on the Loess Plateau of China.

Age (years)	Plant height (m)	Height below canopy (m)	Crown height (m)	Crown width (m)	inter-row distance (m)	Intra-row distance (m)	Maximum LAI ($m^2 m^{-2}$)
3	2.30	0.83	1.80	0.80	5.00	4.00	0.32
5	2.80	0.80	2.20	1.30	5.00	4.00	0.67
8	3.20	0.65	2.50	2.00	5.00	4.00	1.26
10	3.50	0.65	3.10	2.80	5.00	4.00	2.12
12	4.00	0.65	3.60	4.20	5.00	4.00	2.50
15	4.10	0.60	3.80	5.60	5.00	4.00	2.92
20	4.10	0.75	3.60	6.20	5.00	4.00	3.48

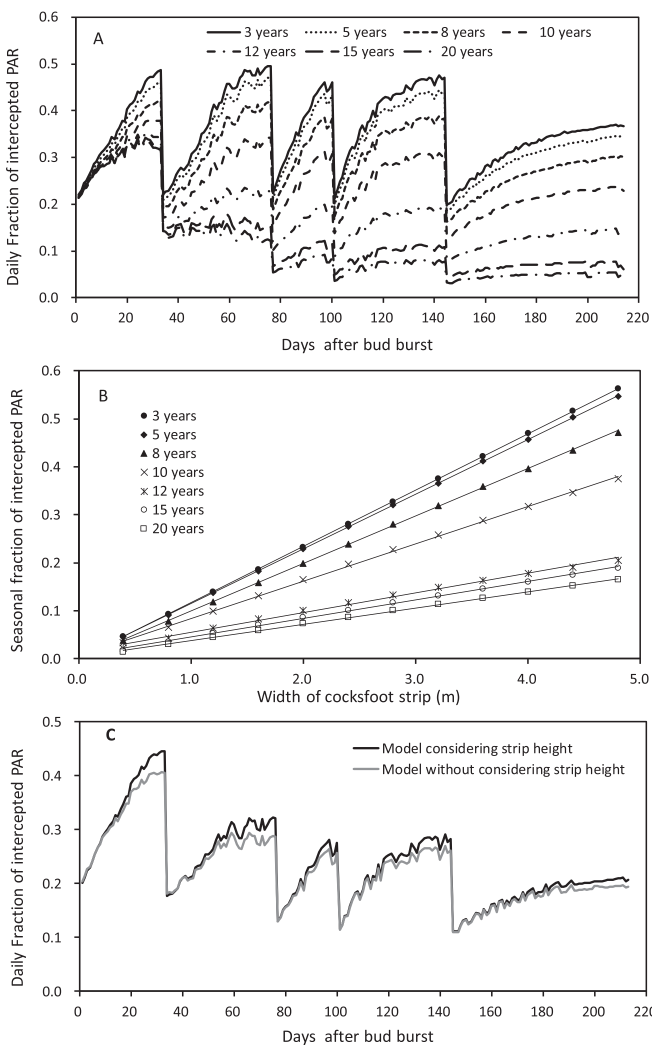

Fig. 10. Fraction of PAR interception by cocksfoot strip as affected by canopy structure. Canopy information of cocksfoot was the data in LC treatments in 2016 and that of apple tree was derived from a study by Wang et al. (2010). (A) Daily fraction of intercepted PAR in different aged apple orchards, (B) seasonal averaged fraction of intercepted PAR as influenced by strip width, and (C) seasonal courses of daily fraction of PAR interception calculated with understorey radiation models considering and without considering strip height.

on past works (Charlesedwards and Thorpe, 1976; Wang et al., 2017c). The light model is based on the Beer's law and takes account of the geometrical relationships between beam direction and the canopy structure, it therefore is very convenient in calculating the radiation transmitted by heterogeneous canopies at any given time. At the same time, the geometrical model could simulate spatial availability of radiation under the tree canopy, which is essential for evaluating understorey crop resource use and production in agroforestry. Model inputs are easy accessible parameters such as local time and position, crown profile, tree LAI and the light extinction coefficient, which insure the practical applicability of the model.

Beam transmission path in the tree canopy has many possibilities as affected by beam angle and canopy structure. Some relevant models presented complex procedures to ascertain it for different situations (Talbot and Dupraz, 2012; Ghezehei et al., 2015), but an influencing area was defined in our present work to simplify the calculation. The area is in relation with the maximum height of tree and the minimum beam elevation. For beam with an elevation below the minimum beam elevation it is supposed to be totally intercepted by the tree and the transmittance would be zero. This assumption is practical since the beam with a very low elevation transmits lots of trees on its way, so its transmission distance is very long. The higher the tree canopy, the greater the influence area. A circle area with a radius of 20 m was ascertained in this work, the 73 trees within it affects the radiation incidence under the target tree. If the target tree is near the border of the orchard, the procedure is also valid, the only difference is that some trees are not existing in the influence area and the calculation is simplified.

Radiation transmission in the understorey is calculated with statistical models. Incident radiation on the cocksfoot surface level is heterogeneous on both row and cross-row direction, geometrical models for estimating radiation transmitted onto soil surface that considering radiation intensity and transmission path ways would be very complex. If the cocksfoot canopy was controlled to keep a relatively low coverage throughout the season, crop strips and path would have little interaction in light interception and the Beer's law could be directly used to calculate light interception. But if the canopy height of cocksfoot was comparable with the path width, this way would lead to large error, and the strip-path radiation model was suggested to be used. The strip-path radiation model has been widely used to calculate radiation partitioning in strip-intercropping systems (Ozier-Lafontaine et al., 1997; Tsubo and Walker, 2002; Zhang et al., 2008; Wang et al., 2015a), and some works validated that its performance was as well as the geometrical model (Ozier-Lafontaine et al., 1997; Tsubo and Walker, 2002). The model considers the interaction between crop and bare strips and was validated to be a useful tool to quantify radiation partitioning between cover crop and soil under the apple tree canopy.

The LAI of apple tree was always below 2.0 $m^2 m^{-2}$ during the two seasons in our experiment, so the spatial distribution of the transmitted radiation was quite variable throughout the day. Data collected on the four directions below the tree crown were averaged to compare with the corresponding simulated values at each measuring hours. The large variability in the amount of light could reduce the accuracy of the model, so the modeling performance was better in the morning and afternoon compared with noon hours. Large variability of light under cover crop strips was attributed to both the variable incident light and the uneven distribution of cover crop plants over the plots. Despite of these factors, the simulated values harmonized with the measurements as a whole, and statistics results were comparable with previous studies for crop intercropping (Tsubo and Walker, 2002; Munz et al., 2014a; Wang et al., 2017c), indicating that the model captured the main factors influencing radiation transmission in tree–cover crop intercropping and was reliable in radiation transmission simulation.

The plant growth and yield advantage in agroforestry systems is affected by temporal and spatial complementarity on resource use. Spatial configuration strongly influence the inter-specific interactions both above and belowground. The nearer the understorey crop strip to the tree row, the severer competition is between the two species (Wang et al., 2017b). For the apple tree and cocksfoot intercropping in this study, cocksfoot showed no adverse effects on the canopy development and yield of the apple tree. This is similar with the yield performance of an apricot orchard in semi-arid condition where cover crop strip is 1.0 m away from the tree row (Bai et al., 2016). The possible reason is that cocksfoot strip is 0.8 m away from the tree trunk and the root is shallow distributed, water depletion in cocksfoot root zones has little effects on average soil water content in the tree root zone. Ramos et al. (2010) also claimed that only significant water extraction by the cover crop could affect the orchard development and productivity.

Fraction of light transmitted through the tree canopy was as high as 0.80 at the initial stage, which maintained a value of around 0.4 in the middle and late season, and the seasonal cocksfoot interception was about 0.25 in our experiment. An appreciable amount of grass was harvested, which is very helpful for the local household sheep husbandry, especially in the spring and early summer seasons when the forage is short (Zhang et al., 2018; Yang et al., 2018). Simulations showed that light interception of the cover crop decreased with ongoing tree age, and there is a sharp decrease from 10 to 15 years old orchard, indicating that grass production in the 15 years or older orchards would be very limited and the main function of cover crop is soil and water conservation. For 12 years or younger orchards, forage crop is suggested to be cultured to produce forage and provide other ecological services, the crops strip should be designed after considering inter-specific water competition.

Frequent cutting effectively reduced the LAI of cocksfoot by 34.0% and 33.3% respectively in 2016 and 2017, but the corresponding reduction in light interception were only 13.1% and 12.9%. The effects of cutting frequency on the production of forage is uncertain, repeatedly cutting would stimulate the recovery growth and give positive effects but heavy cutting might reduce the growth potential and the final total production (Collins and Balasko, 1981; Walter, 1991). We found that the light use efficiency of cocksfoot in frequent cutting treatment was increased by 28.2% and 67.2% respectively in 2016 and 2017, which made the cocksfoot in LC plots produced more dry biomass with less light interception compared to the GC treatments. Light use efficiency is also in relation with the availability of water and nutrient (Albaugh et al., 2014; Munz et al., 2014b; Wang et al., 2015b). Spring drought in 2017 severely constrained the light conversion processes in cocksfoot. The study by Centinari et al. (2013) indicated that evapotranspiration of cover crop is linearly related with radiation availability for it, and it could be remarkably reduced by frequent cutting. The water extraction of cocksfoot strip in the GC must be greater than that in LC, but their difference was insignificant compared to the total water use of the agroforestry system, so their effects on apple tree growth and production were also not significantly different. This sentence has been rephrased. Soil evaporation in clean tillage is a main water consumer during rainy seasons and many studies have indicated the water conservation advantage of cover crops (Gómez et al., 2009; Gao et al., 2013b; Palese et al., 2014), so it is possible to reduce understorey water use by proper cover crop management in semi-arid environment.

5. Conclusions

A model to calculate radiation partitioning in tree and strip-planted crop intercropping was constructed and validated. About 25% incoming PAR was intercepted through planting cocksfoot in a 11–12 years old apple orchard on the Loess Plateau of China. Light use efficiency and biomass production of cocksfoot were far greater in the frequent cutting treatment. Planting cover crop showed no adverse effects on apple production. Simulations showed that seasonal fraction of light interception by cocksfoot strip under 3–10 years old apple trees varied from 0.41 to 0.25, and was < 0.15 for 15 years and older orchards. The light transmission model presented in this work could be used to evaluate water partitioning and use efficiency in the fruit tree and cover crop intercropping under semi-arid environments. Radiation transmission model should be combined with other processes-based models to optimize cover crop planting and manage practices in the future work.

Acknowledgements

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