

IMPACT OF TREE-THINNING ON FOLIAR CHLOROPHYLL FLUORESCENCE PARAMETERS OF OPEN-CENTRAL APPLE TREES

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Key words: Apple orchard, Tree-thinning, Leaves, Chlorophyll fluorescence

Abstract

Impact of tree-thinning on the diurnal variation, light response curve and its fitting parameters of foliar chlorophyll fluorescence of open-central apple trees was investigated in orchards in China. Compared to the un-thinned control, tree-thinning increased the foliar photosynthetic active radiation (PAR) and PSII electron transport rate (ETR), and maintained the quantum yield of non-regulated heat dissipation and low fluorescence emission (Y(NO)) during the whole day. Under variable intensities of PAR, the thinning treatment enhanced foliar ETR and effective photochemical quantum yield of PS II (Y(II)), decreased the quantum yield of light-induced non-photochemical fluorescence quenching (Y(NPQ)), and maintained the low Y(NO). The thinning also boosted the foliar maximum electron transport rate (ETR_{max}) and the minimum saturating irradiance (I_k). Tree-thinning improved the light conditions in the canopy of open-central apple trees, resulting in increased foliar ability to utilize the solar energy.

Introduction

The open-central apple tree has been a new apple tree shape in recent years in China in the reformation of condensed central-leader tree-shaped orchards and is the tree shape with a horizontal leaf canopy that can be achieved from the “trunk-up” and “top-down” of the central-leader trees (Zhang and Niu 2004). This type of tree shape can improve light reception in the canopy to increase the photosynthetic efficiency (Niu *et al.* 2002), resulting in better fruit quality and greater yield (Yang *et al.* 1998, Wei *et al.* 2004, Zhang *et al.* 2007, Widmer and Krebs 2001). However, apple orchards with this type of tree shape are usually condensed with vigorous trees, causing tree shading each other especially in the full production stage (Yuan *et al.* 2010). Thus, tree-thinning has to be used to improve the light condition in the orchards.

Experimental results showed that the apple tree-thinning significantly improved the light condition in orchards, greatly increased photosynthetic efficiency and dramatically enhanced fruit quality (Wu *et al.* 2012, Zhang *et al.* 2009, Nie *et al.* 2011, Li and Yang 2007). Photosynthetic capacity is the foundation of fruit yield and quality (Asada and Arakawa 2000, Green *et al.* 2001), whereas chlorophyll fluorescence is closely related to the light absorption, transport, dissipation and distribution during photosynthesis (Maxwell and Giles 2000). The present study was undertaken to assess the effect of tree-thinning on the diurnal variation, light response curve and its fitting parameters of foliar chlorophyll fluorescence of open-central apple trees.

Materials and Methods

Experimental apple orchards were located in Wanrong county of Shanxi province, China. The apple trees were 18 years old (*Malus domestica* Borkh cv. Naganofuji No. 2 grafted on *Mallus*

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micromalus Makino). Trees were originally in small canopy central-leader shape. In 2005, these trees were changed to small canopy open-central shape through the “trunk-up” and “top-down” of the central-leader trees. The thinning treatment was made in 2009 by removing the alternate row. In the un-thinned orchard (control), distance between trees was 3 m and that between rows was 4 m with a south-north row direction, while in the thinned orchard, row distance was 8 m. Orchards were in sandy-loam soil and maintained uniformly in standard cultural practice. Structure parameters of apple trees after the winter-pruning in 2013 in the thinned and un-thinned orchards were as follows: trunk height 1.5 - 2.0 m, trunk perimeter 65 - 75 cm, tree height 350 - 450 cm, main branches 4 - 5, total branches 500-600, canopy diameter (east-west or north-south) 4.0 - 5.0 m.

In early June 2014, diurnal variation of the foliar chlorophyll fluorescence parameters was measured in a clear sunny day. Three representative trees were selected from the un-thinned and thinned orchards, respectively. Two fully expanded leaves, each from the 5th or 6th leaf (counted from the tip) on an one-year growing shoot located at about 50 cm from bottom and periphery of the canopy on the east and west sides of each tree were selected for the measurement. The measurement for each of the leaves was taken at 8 : 30, 10 : 30, 12 : 30, 14 : 30 and 16 : 30 hours with a PAM-2500 Portable Chlorophyll Fluorometer (WALZ, Germany). The photosynthetic active radiation (PAR), leaf surface temperature (T_{mp}), effective photochemical quantum yield of PS II (Y(II)), quantum yield of light-induced non-photochemical fluorescence quenching (Y(NPQ)), quantum yield of non-regulated heat dissipation and fluorescence emission (Y(NO)) and electron transport rate (ETR) were read or calculated and then recorded [(Y(II)+Y(NPQ)+Y(NO))=1, ETR=PAR×Y(II)×0.84 ×0.5].

Responses of the chlorophyll fluorescence parameters to variable PAR for each of the above selected leaves were also measured. The measurement was carried out from 10:00 to 11:00 hour with the PAM-2500 Portable Chlorophyll Fluorometer. Prior to the measurement, following PAR levels were set: 0, 1, 30, 100, 197, 362, 618, 980, 1385 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. After a short time of dark adaptation, the leaves were respectively illuminated by the 9 PAR levels (from low to high) and a short saturation pulse of light was given at the end of the serial illumination. The resulting Y(II), Y(NPQ), Y(NO) and ETR were read or calculated and then recorded. The initial slope of rapid light curve (α), the maximum electron transport rate (ETR_{max}) and the minimum saturating irradiance (I_K) were calculated based on a method as described by Eilers and Peeters (1998).

Results and Discussion

During the day, PAR of east and west sides of trees in the thinned orchard increased in the morning but decreased in the afternoon (Fig. 1A). In the east side, PAR reached 800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 8:30, then gradually increased to more than 1700 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during 10:30 - 12:30. Thereafter, it gradually decreased to 165 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 16:30. In the west side, PAR was less than 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 10:30, rapidly reached to 1654 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 12:30, and then gradually reduced as that in the east side (Fig. 1A). Either in the east or west side, PAR in the un-thinned control was below 60 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during the day.

Fig. 1B showed that T_{mp} of apple leaves increased from morning, reached to its peak value at the mid-day, and then gradually decreased. At 12:30, T_{mp} of the east and west sides of trees was over 4°C higher in the thinned orchard than in the un-thinned orchard.

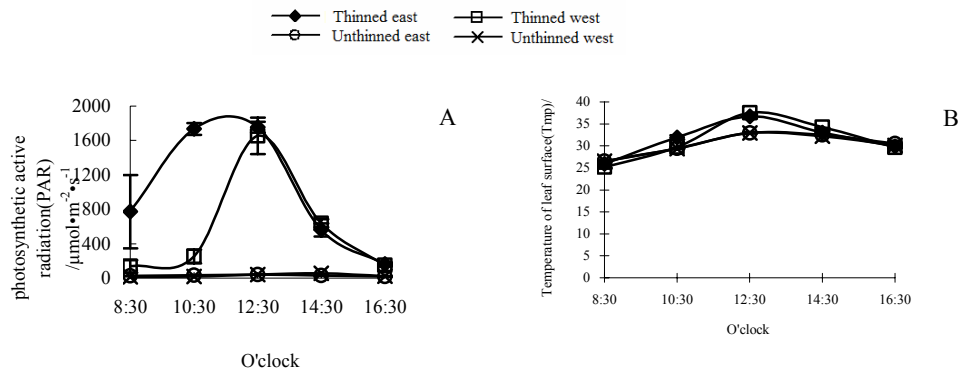


Fig. 1. Daily variation of photosynthetic active radiation (PAR) (A) and leaf temperature (Ttmp) (B) in the east and west sides of apple trees in thinned and un-thinned orchards.

Fig. 2A showed that Y(II) of leaves maintained constantly high in both sides of the trees in the un-thinned orchard during the whole day, but it was lower (especially at noon) in both sides in the thinned orchard.

Fig. 2B demonstrated that ETR in leaves were much greater in the east or west side of trees in the thinned orchard than in the un-thinned control. In the thinned orchard, foliar ETR was greater in east side than in the west side during the morning, and the peak ETR appeared in the east was earlier than that of the west. The trends of ETR were similar to those of PAR (Fig. 1A). This is due to the fact that ETR was calculated from PAR ($\text{ETR} = \text{PAR} \times \text{Y(II)} \times 0.84 \times 0.5$).

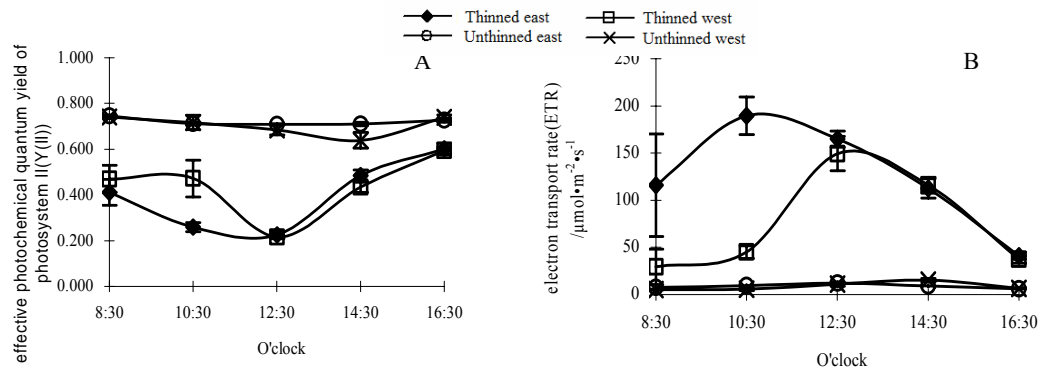


Fig. 2. Daily variation of effective photochemical quantum yield of PS II (Y(II)) (A) and PSII electron transport rate (ETR) (B) in leaves of east and west sides of apple trees in thinned and un-thinned orchards

Fig. 3A showed that Y(NPQ) of leaves in the east and west sides of trees was higher in the thinned orchard than in the un-thinned control at most time of the day. The trend of Y(NPQ) in the thinned orchard was increasing in the morning, reaching its peak at the mid-day and decreasing gradually in the afternoon, opposite to that of Y(II), suggesting that more light energy was dissipated as heat because of the excessive PAR (Fig. 1A) and the high foliar Tmp (Fig. 1B) during the mid-day.

Fig. 3B showed that $Y(NO)$ s in the east and west sides of trees in the thinned and un-thinned orchards were almost similar and the values were constantly low during the day.

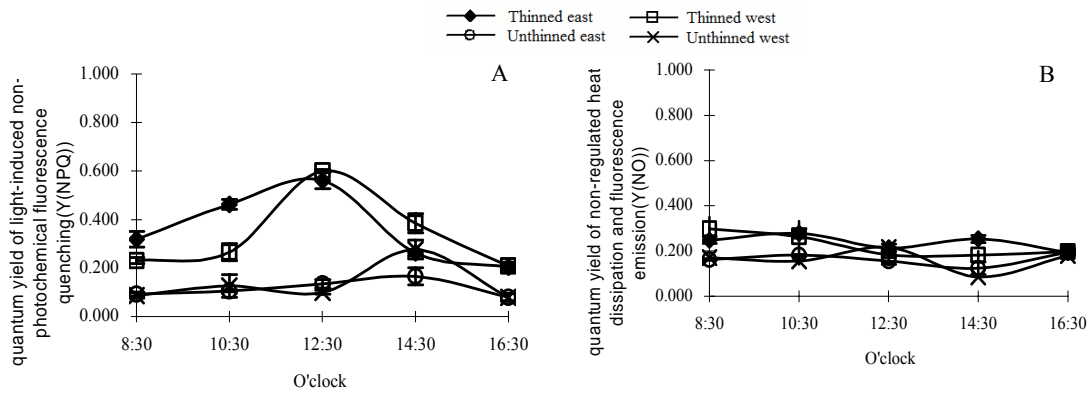


Fig. 3. Daily variation of quantum yield of light-induced non-photochemical fluorescence quenching ($Y(NPQ)$) (A) and quantum yield of non-regulated heat dissipation and fluorescence emission ($Y(NO)$) (B) in leaves in the east and west sides of apple trees in thinned and un-thinned orchards

Fig. 4 showed that the $Y(II)$ decreased gradually as the PAR increased. With the exception when the PAR was very low, foliar $Y(II)$ under the same PAR level in the east and west sides of trees was higher in the thinned orchard than in the un-thinned. $Y(II)$ in the thinned orchard was also higher in east side than in the west side (Fig. 4A).

With the increase of PAR, ETR increased gradually (Fig. 4B). The exception was found when the PAR was very low. ETRs at the same PAR level were higher in the thinned than un-thinned orchard, and the ETR was higher in the east side than the west side (Fig. 4B).

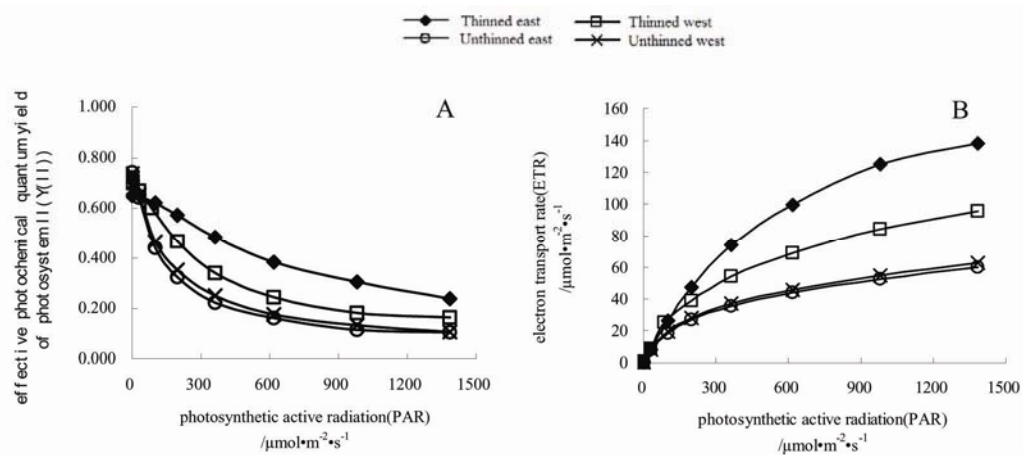


Fig. 4. Response of effective photochemical quantum yield of PS II ($Y(II)$) (A) and PSII electron transport rate (ETR) (B) to photosynthetic active radiation (PAR) in leaves of east and west sides of apple trees in thinned and un-thinned orchards.

When PAR was very low, Y(NPQ) was closed to 0 and with the increase of PAR, Y(NPQ) increased gradually (Fig. 5A). At the same PAR level (>300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), Y(NPQ) was greater in the un-thinned trees compared to the thinned trees (Fig. 5A).

Fig. 5B indicated that with the increase of PAR, Y(NO) quickly raised to a stable level and then maintained constant. Y(NO)s of trees in the thinned and un-thinned orchards were similar, suggesting that the excessive light energy caused by thinning was quenched as heat, resulting in no damage to the PSII.

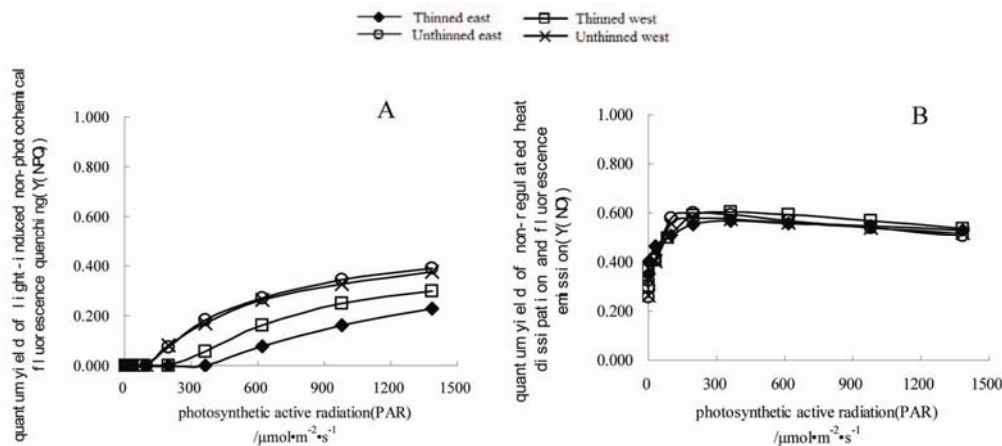


Fig.5. Response of the quantum yield of light-induced non-photochemical fluorescence quenching (Y(NPQ)) (A) and quantum yield of non-regulated heat dissipation and fluorescence emission (Y(NO)) (B) to photosynthetic active radiation (PAR) in leaves of east and west sides of apple trees in thinned and un-thinned orchards.

Foliar α in east and west sides of trees in the thinned and un-thinned orchards was almost similar (Table 1). Thus, thinning had no effect under weak light on light utilization efficiency of apple leaves.

ETR_{max} was far greater in both sides of trees in thinned orchard than in the un-thinned and was higher in the east than in the west (Table 1).

Foliar I_K of apple trees was greater in thinned orchard than the un-thinned and it was greater in the east side in both thinned and un-thinned orchards. Improved adaptation to strong light by leaves in the thinned orchard may be related the stronger PAR (Fig. 1A) received during the whole day.

Table 1. Fitting parameters of rapid light curve (RLC) in leaves of east and west sides of apple trees in thinned and un-thinned orchards.

	Thinned east	Thinned west	Un-thinned east	Un-thinned west
Initial slope of rapid light curve(α)/ $e^-/h\nu$	0.299	0.263	0.28	0.267
Maximum electron transport rate (ETR_{max})/ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	152.4	116.9	69.1	71.6
Minimum saturating irradiance(I_K)/ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	510.3	444.7	339.3	268.2

Tree thinning strongly influenced light condition in orchards (Yang *et al.* 2012). Previous reports indicated that thinning of vigorous trees in an apple orchard significantly increased the light intensity in the remaining trees (Ruan *et al.* 2011), while thinning of pear trees also improved the solar radiation, especially during the mid-day (Niu *et al.* 2011). The results of this investigation (Fig. 1A) were consistent with these reports. The increased foliar Tmp by thinning during the mid-day (Fig. 1B) may be resulted from the enhancement of solar radiation.

Previous reports showed that, foliar Y(II) of some wooden plants well-adapted to strong solar radiation such as pecan (Xu *et al.* 2007), kapur (Meng *et al.* 2005) and populus (Luo *et al.* 2006) decreased during the mid-day, while the non-photochemical quenching coefficient NPQ and the Y(NPQ) increased. Present finding from the thinned orchard (Figs 2A, 3A) were found consistent with these reports, suggesting that open-center trees after thinning had adapted to the stronger light in the orchard. Foliar Y(NO) in both thinned and un-thinned orchards was low with no dramatic variation during the day (Fig. 3B), indicating that thinning-caused increase of PAR (Fig. 1A) had no damaging effect to the remaining trees. ETR is closely related to PAR and Y(II). After thinning, ETR in the orchard increased dramatically, consistent with daily trends of PAR and the decrease of Y(II) had no effect on the trends of ETR (Figs 1A, 2A, B).

Plant can adapt to variable light intensity by a regulation of photosynthetic apparatus and photosynthetic function and this regulation can be represented by the responsive parameters of chlorophyll fluorescence to PAR (Han *et al.* 2010). With the increase of PAR, foliar Y(II) and Y(NPQ) in both un-thinned and thinned orchards decreased and increased, respectively (Figs. 4A, 5A). This was because the PSII light-captured complex (LHCII) efficiently captured light energy under weak light, but the dissipation of excess light energy was increased as the saturation of light reached (Horton *et al.* 2008). This mechanism also explained the light saturation of PAR-ETR curve (rapid light curve (RLC)) (Fig. 4B). At the same PAR, more excited light energy in leaves in the thinned orchard was used for photochemical reaction (Y(II)) but the Y(NPQ) was reduced and the Y(NO) kept constant to prevent leaves from the light damage (Figs 4A, 5A, B). These results agree to those in the light and shade treatment experiment of watermelon (Sun and Wang 2007) and *Ulmus pumila* (Han *et al.* 2010) leaves, suggesting that the greater light utilization efficiency in the thinned orchard was resulted from the enhanced transmittance (Li *et al.* 2012) and PAR (Zhang *et al.* 2009). ETR comes from the multiplication of PAR, Y(II) and the related coefficient. For investigation of plant photosynthetic capacity, therefore, ETR should be assessed (Beer *et al.* 1998).

The fitting analysis of RLC revealed that the thinning had little effect on foliar α but increased ETR_{max} and I_K (Table 1), suggesting that thinning had little effect on the light utilization capability in leaves under weak light, but increased the maximum light utilization capability and the adaptation to strong light in leaves. Chlorophyll fluorescence parameters can reflect a long-term effect of light condition on leaves (Cai *et al.* 2005, Ralph and Gademann 2005). The fitting analysis of RLC also demonstrated that apple leaves in the thinned orchard were well adapted to weak and strong light (Table 1). This may be resulted from the large variation of PAR during the day (Fig. 1A).

At the same PAR, the thinning caused the increase in Y(II), ETR and the decrease in Y(NPQ) may be related to the long-term adaptation of leaves to strong light (Wagner *et al.* 2008). Thus, no light-damage occurred to leaves (Figs 4A, B, 5A, B). Results from diurnal variation of the parameters indicated that the thinning reduced the Y(II) but boosted the ETR and Y(NPQ), and the changes were most prominent during the mid-day (Figs 2A, B, 3A). This was the adaptation of plants to the increased PAR for protection of the photosynthetic apparatus from the damage (Demming-Adams and Adams 1992). Therefore, no damage to leaves occurred by the excessive light energy (Fig. 3B). The decrease of foliar Y(II) in the thinned orchard did not mean the

reduction of net photosynthetic rate. Because the thinning largely enhanced the PAR and ETR, the related photophosphorylation was promoted, leading to the greater generation of ATP and NADPH which provided more reducing power to the dark reaction (Lawlor and Mitchell 1991, Pewttersen and McDonald 1992) (Figs 1A, 2A, B).

In conclusion, the tree-thinning in apple orchard with open-central trees increased PAR to the trees. These trees then adapted to the stronger light in order to be capable of using the increased light energy. Further research in the field will provide advanced theoretical basis for management of apple orchards with open-central trees producing greater yield and quality fruit.

References

- Asada T and Arakawa O 2000. The analysis of light interception and leaf area index (LAI) in central leader 'Fuji/M26' and 'Jonagold/26' apple orchards producing high yields and quality fruit. *Acta Hort. Sin.* **525**: 421-423.
- Beer S, Vilenkin B, Weil A, Veste M, Suel L and Eshel A 1998. Measuring photosynthetic rates in seagrasses by pulse amplitude modulated (PAM) fluorometry. *Mar. Ecol-Prog. Ser.* **174**: 293-3.
- Cai ZQ, Rijkers T and Bongers F 2005. Photosynthetic acclimation to light changes in tropical monsoon forest woody species differing in adult stature. *Tree Physiol.* **25**(8): 1023-1031.
- Demming-Adams B and Adams WW 1992. Photoprotection and other responses of plants to high light stress. *Annu Rev Plant Physiol Plant Mol. Biol.* **43**: 599-626.
- Eilers PHC and Peeters JCH 1998. A model for the relationship between light intensity and the rate of photosynthesis in phytoplankton. *Ecol. Model.* **42**: 199-215.
- Green SR, Greer DH, Wunsche JN, Caspari H and Palmer JW 2001. Measurements of light interception and utilization in apple orchard. *Acta Hort. Sin.* **557**: 369-376.
- Han W, Xu XW, Li L, Li SY, Luo YX, Zhou Y and Guo LL 2010. Variation of rapid light curves of *Ulmus pumila* leaves after high-light and low-light acclimation. *Arid Zone Res.* **27**: 738-744. (in Chinese)
- Horton P, Johnson MP, Perez-Bueno ML, Kiss AZ and Ruban AV 2008. Photosynthetic acclimation: does the dynamic structure and macro-organization of photosystem II in higher plant grana membranes regulate light harvesting state? *FEBS J.* **275**: 1069-1079.
- Lawlor DW and Mitchell RAC 1991. The effects of increasing CO₂ on crop photosynthesis and productivity: a review of field studies. *Plant Cell Environ.* **14**: 807-811.
- Li PH, Wu JS, Dong XY, Wang JZ, Xue XM and Lu C 2012. Effects of different thinning methods on illumination, photosynthetic, growth and fruiting in airtight apple orchard. *Sci. Agric. Sin.* **45**: 2217-2223. (in Chinese)
- Li ZD and Yang JD 2007. Thinning and tree-form transformation on the yield and quality of 'Fuji' apple canopy. *China Fruits* **3** (2): 39-40. (in Chinese)
- Luo QH, Li ZJ, Wu WM and Han L 2006. Comparative study of photosynthetic and chlorophyll fluorescence characters of *Populus euphratica* and *P. pruinosa*. *Acta Bot. Boreali-Occidentalia Sin.* **26**: 983-988. (in Chinese)
- Maxwell K and Johnson Giles N 2000. Chlorophyll fluorescence - A practical guide. *J. Exp. Bot.* **51**(345): 659-668.
- Meng LZ, Zhang JL, Cao KF and Xu ZF 2005. Diurnal changes of photosynthetic character and chlorophyll fluorescence in canopy leaves of four diptocarp species under ex-situ conservation. *Acta Phytoecol. Sin.* **29**: 976-984. (in Chinese)
- Nie PX, Xue XM, Wang JZ, Yang ML, Huang CY 2011. Study on the thinning effect in high-density apple orchards. *Shandong Agric. Sci.* **5**: 37-39. (in Chinese)
- Niu ZM, Yu L, Jiang YF and Wang JX 2011. Effect of tree-thinning on transmittance of solar radiation in pear orchard. *J. Shanxi Agric. Sci.* **39**: 1252-1255, 1259. (in Chinese)
- Niu ZM, Zhang DP, Zhan JC and Wang JH 2002. Influence of some interrelated physiological factors on the net photosynthetic rate of apple leaves. *Proceeding of International Apple Symposium, Taian*, 265-272.

- Pewterson R and McDonald AJS. Effects of elevated carbon dioxide concentration on photosynthesis and growth of small birch plants (*Betula pendula* Roth) at optimal nutrition. *Plant Cell Environ.* **15**: 911-919.
- Ralph PJ and Gademann R 2005. Rapid light curves: A powerful tool to assess photosynthetic activity. *Aquat. Bot.* **82**(3): 222-237.
- Ruan BL, Liu JH, Li XW, Li BZ, Han MY, Zhang LS and Zhou YB 2011. Effects of different thinning methods on light penetration, leaf character and fruit quality in an over-crowd 'Fuji' apple orchard with standard rootstocks. *Sci. Agric. Sin.* **44**: 3805-3811. (in Chinese)
- Sun YP and Wang LJ 2007. Effects of 5-aminolevulinic acid (ALA) on chlorophyll fluorescence dynamics of watermelon seedlings under shade condition. *Acta Hort.* **34**: 901-908. (in Chinese)
- Wagner R, Dietzel L, Bräutigam K, Fischer W and Pfannschmidt T 2008. The long-term response to fluctuating light quality is an important and distinct light acclimation mechanism that supports survival of *Arabidopsis thaliana* under low light conditions. *Planta* **228**: 573-587.
- Wei QP, Lu RQ, Zhang XC, Wang XW, Gao ZQ and Liu J 2004. Relationships between distribution of relative light intensity and yield and quality in different canopy shapes for 'Fuji' apples. *Acta Hort.* **31**: 291-296. (in Chinese)
- Widmer A and Krebs C 2001. Influence of planting density and tree form on yield and fruit quality of 'Golden delicious' and 'Royal Gala' apples. *Acta Hort.* **557**: 235-241.
- Wu JS, Dong XY, Duan YX, Wang JZ and Li PH 2012. Effects of different thinning methods on group structure and fruit quality in an airtight apple orchard. *Chinese Agric. Sci. Bull.* **28** (19): 135-140. (in Chinese)
- Xu DC, Lu FD and Liu XY 2007. Studies on the diurnal variation of chlorophyll fluorescence parameters of different pecan varieties. *Acta Laser Biol. Sin.* **16**: 259-265. (in Chinese)
- Yang F, Gao MD, Yu B and Ma CM 2012. Effects of environmental changes on plant diversity after thinning. *Hebei. J. Forest Orchard Res.* **27** (2): 126-131. (in Chinese)
- Yang ZW, Zhou YW, Fu Y, Yang MN and Zhang TS 1998. Relationship between microclimatic character of different crown types and fruit quality of "Fuji" apple. *Chinese J. Appl. Ecol.* **9**: 533-537. (in Chinese)
- Yuan JJ, Zhao ZY, Wan YZ, Mei LX and Yang P 2010. Effects of tree-thinning and reshaping on production and fruit quality of Red 'Fuji' apples in the mid-aged and condensed orchards. *J. Northwest A & F Univ. (Nat. Sci. Ed.)* **38** (4): 133-137, 142. (in Chinese)
- Zhang JX, Wei QP, Zhang J, Wang LX, Wang CL, Sun XP and Song K 2009. Leaf photosynthetic potential in canopy layers of un-thinned and thinned apple orchards. *Chinese J. Appl. Ecol.* **20**: 2898-2904. (in Chinese)
- Zhang WH and Niu ZM 2004. Pruning techniques on small open-center tree shape of apple. Beijing: China Agricultural Press. (in Chinese)
- Zhang XC, Gao ZQ, Fu ZF, Fang JH and Li TH 2007. Influences of tree shape reconstruction on the canopy structure and photosynthesis of apple. *Acta Hort.* **34**: 537-542. (in Chinese)

(Manuscript received on 11 September, 2015; revised on 29 November, 2015)