

Comprehensive Decision-Making for the Leaf-to-Fruit Ratio and Estimation of Economic Output Value of Walnut Trees Based on Statistical Analyses

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Abstract

This study examined the *Juglans regia* ‘Xinxin2’ walnut variety using combined field control experiments with laboratory chemical analyses and analyzed the effects of the relationships among net photosynthetic rate (Pn), specific mass transfer rate (SMTR), nut dry mass (NDM), and nut yield per girdled fruit-bearing shoot (Yield) on the leaf-to-fruit ratio (LFR). We used comprehensive decision-making based on mathematical programming to determine the optimal LFR for this walnut variety in the peak fruiting stage. The optimal LFR was calculated as the comprehensive expected value of the linear combination among the equations for the effects of LFR on the Pn, SMTR, NDM, and Yield and was determined to be 2.02. Compared with walnut plants without LFR adjustment, the walnut plants with LFR adjustment using 2.02 as the minimum threshold had a 19.52% lower nut yield, a higher nut quality (Special Class, Class I, and Class II accounted for 100% of the nut yield per 670 m²), and a 36.22% higher economic output value per 670 m². This study indicates that improving fruit quality to produce Grade I and II nuts will increase economic output, although the total yield will decrease when managing efficient LFR in nut production.

Additional key words: artificial manipulation, regression analysis, residual analysis, source-sink relationship

Introduction

The production efficiency of fruit trees is determined by their assimilation, transport, and utilization of carbohydrates (Lenz, 1979). Furthermore, fruit tree yield and fruit quality are dependent on the interactions between its sources and sinks (Peng et al., 2012). The regulation of source-sink relationships, usually the leaf-to-fruit ratio (LFR), essentially involves regulating the equilibrium between vegetative growth and reproductive growth by controlling the partitioning of carbohydrates (Lakso and Flore, 2003). Some studies have shown that an excessively high fruit load may decrease the sugar content of fruits, the growth and viability of the root system, the maturity of new shoots, and the germination rate in the second year (Lou, 2005). However, excessive fruit thinning leads to excessive sprouting and overgrowth of summer shoots, aggravates the contradiction in nutrient partitioning between

Received: February 21, 2020

Revised: April 30, 2020

Accepted: June 7, 2020

 OPEN ACCESS



HORTICULTURAL SCIENCE and TECHNOLOGY
38(4):429-439, 2020
URL: <http://www.hst-j.org>

pISSN : 1226-8763
eISSN : 2465-8588

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This experiment was funded by Natural science project of scientific research plan of universities in Xinjiang Uygur Autonomous Region ‘Study on the relationship between carbohydrate assimilation and distribution and leaf fruit ratio of walnut’ (XJEDU2019Y016).

shoots and fruits, increases the tendency for fruit shedding, and eventually causes a decline in fruit tree yields (Li, 2008). Therefore, to achieve high-yield and high-quality production in fruit trees, it is necessary to determine a reasonable load for fruit trees. In addition, it is important to determine what types of source-sink relationships can accelerate the assimilation, transport, and utilization of carbohydrates to the greatest extent and what relationships can improve the yield of fruit trees and fruit quality.

Previous studies on source-sink relationships have mainly focused on their effects on aspects such as the photosynthetic characteristics of leaves (Iglesias et al., 2002; Urban et al., 2004; Bustan et al., 2011, 2016; Bobeica et al., 2015; Moscatello et al., 2017) and fruit quality (Famiani et al., 2000; Guo et al., 2009; Haouari et al., 2013). Current reasonable loads for certain tree varieties are based on what happens during cultivation and management, which lacks a scientific basis with rigorous quantification.

Therefore, this study examined the *Juglans regia* 'Xinxin2' walnut variety using artificial LFR manipulation to analyze the net photosynthetic rate (P_n) of leaves, the specific mass transfer rate (SMTR) of carbohydrates in the carpodium, the nut dry mass (NDM), and the nut yield of girdled fruit-bearing shoots with different LFRs. A comprehensive decision-making method using linear mathematical programming was applied to determine the optimal LFR threshold for *J. regia* 'Xinxin2' during the peak fruiting stage.

Materials and Methods

Experimental Site and Plant Materials

This study was carried out in a walnut orchard located in Southern Xinjiang, China (41°11'06.31"-41°12'47.74"N, 79°12'12.76"-79°13'57.87"E; 1,394 masl). The experimental site has a mild, arid climate with a mean annual temperature of 9.4°C and an average rainfall of 91.5 mm. Uniform 10-year-old walnut trees (*Juglans regia* L. 'Xinxin2') planted at a distance of 5 m × 6 m in the east-west direction were used in this study.

Sink-Source Manipulation

After fruit set, defoliation, girdling, and defruiting were performed on 150 sun-exposed shoots with fully expanded leaves and developing fruit in the south of 10 trees. Fifteen shoots were treated with 15 LFRs (1L:1F, 1L:2F, 1L:3F, 2L:1F, 2L:2F, 2L:3F, 3L:1F, 3L:2F, 3L:3F, 4L:1F, 4L:2F, 4L:3F, 5L:1F, 5L:2F, 5L:3F) per tree (Fig. 1). Three single-tree replications per ratio were selected for determination of carbohydrate assimilation rate. The remaining seven trees were sampled to measure the carbohydrate transport rate and utilization.

Determination of Net Photosynthetic Rate (P_n)

P_n was used to express carbohydrate assimilation rate. During growing seasons, P_n was measured between 11:00 and 13:00 per day, 7 d, 22 d, 52 d, 82 d, and 107 d after LFR regulation (30 d, 45 d, 75 d, 105 d, 130 d after full bloom of female flowers). Two fully developed leaves per LFR close to the fruit were placed in the leaf chamber to measure P_n ($\mu\text{mol CO}_2/\text{m}^2 \cdot \text{s}^{-1}$) using a portable photosynthesis system (LI-6400XT, LI-COR, USA).

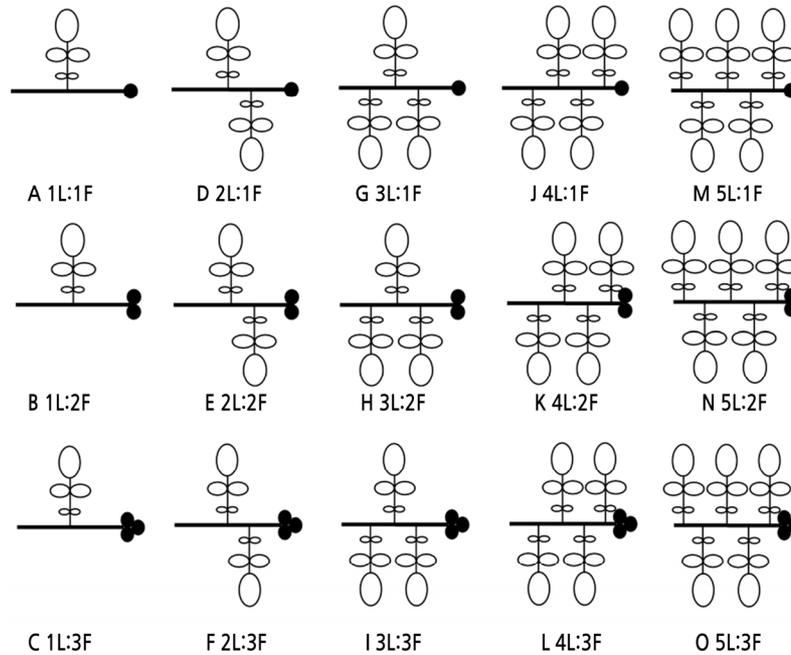


Fig. 1. Different leaf-to-fruit ratio manipulations on the girdled shoots of *J. regia* 'Xinxin2' walnut.

Determination of Specific Mass Transfer Rate (SMTR)

SMTR was used to express carbohydrate transport rate. The carpopodium per LFR was sampled on 7 d and 107 d after LFR regulation and dipped into fixation solution [70% (v/v) ethanol:formaldehyde:glacial acetic acid = 90:5:5] to prepare the paraffin sections. The carpopodium samples were embedded in paraffin and sliced following the protocol of Willey (1971). The section cutting, examination and measurements, and photographing were performed using a rotary microtome (Leica Microsystems RM2265) and a digital camera (DFC495) with image recording, and AutoCAD 2014 was used to process the photos to calculate the phloem area (PA). The procedures were performed in triplicate for each LFR treatment, and five fields of view were observed for each repeat.

Reference was made to the calculation methods for SMTR in Li Hesheng's "Modern Plant Physiology" (2012).

$$SMTR = \frac{M_2 - M_1}{PA \times T \times 24} \quad (1)$$

where SMTR is measured in $\text{g} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$, M_1 is the mass of dried fruit measured at 7 d after LFR regulation (g), M_2 is the mass of dried fruit measured at 107 d after LFR regulation (g), PA is the average of the cross-sectional area of carpopodium phloem between the two measurements (cm^2), and T is the time interval between the two measurements (d).

Determination of Nut Dry Mass (NDM)

At the mature stage, five fruits on the girdled shoots per LFR were peeled off the green skin, dehydrated in an electric thermostatic air-drying oven (DHG-9240A) at 105°C for 30 min, and then dried at 70°C to a constant weight to measure the nut dry mass (NDM).

Regression Analysis

We performed a positive square root transformation on carpodium SMTR (Sqrt SMTR). Linear functions ($y = ax + b$), quadratic functions ($y = ax^2 + bx + c$), and cubic functions ($y = ax^3 + bx^2 + cx + d$) were then employed to establish the regression equations of the LFR effects, whereby the LFR represented the independent variable (x) and the Pn mean at 45, 70, 90, 110, and 130 d after walnut flowering, Sqrt SMTR, and NDM represented the dependent variables (y).

Residual Analysis

To test whether the effect regression equations constructed using the statistical method above were accurate, the χ^2 test, Durbin-Watson (DW) test, and Levene's (W) test were performed on the residuals of the regression equations ($e_{ij} = y_{ij} - \hat{y}_{ij}$) to test their normal distribution, independence, and homogeneity of variance. If the residuals of a regression equation passed the residual normal distribution, independence (without first-order autocorrelation), and homogeneity of variance tests, the hypothesized regression equation was determined to be accurate.

Regression Analysis and Residual Analysis of Yield Effect of LFR

Based on the effect of effective LFR on NDM, the yield effect relationship of nuts per plant based on LFR was designed:

$$Y_i = A_i \times W_i \times N_i \times 450 \quad (2)$$

where Y_i denotes the nut yield of the girdled shoots with an LFR of i (g); A_i denotes the percentage of girdled shoots with an LFR of i among the total number of shoots (%); W_i denotes NDM $_i$, obtained by substituting the LFR $_i$ into the regression equation between LFR and NDM (g); N_i denotes the actual number of fruits on the girdled shoots when the LFR is i ; and 450 denotes the average number of shoots on a single walnut tree based on a survey of 60 walnut trees aged 12a in a natural state.

The Yield calculated by the above equation was first transformed into LngammaYield, whereby the LFR represented the independent variable (x) and LngammaYield represented the dependent variables (y) and refer to the above methods to establish regression relationship and carry out residual analysis.

Establishing and Solving the LFR Comprehensive Decision-Making Objective Function

To determine the optimal LFR of girdled walnut shoots and maximize its comprehensive expected value for Pn, SMTR, NDM, and Yield effects, the linear combination of the Pn, SMTR, NDM, and Yield effect relationships for *J. regia* 'Xinxin2' LFR served as the objective function. The maximum solutions reached by the single expected values for LFR effects on Pn, SMTR, NDM, and Yield were set as the constraints. The maximum solutions reached by the single expected values for LFR effects on Pn, SMTR, NDM, and Yield and the maximum solution reached by the comprehensive expected value (objective function) were then substituted back into the four effect relationships, respectively, to test the validity of the solutions sought by the objective function under the constraints and to determine the optimal LFR.

Comprehensive Decision-Making for the Optimal LFR

Based on the effect relationships between the LFR of girdled shoots and walnut NDM, we estimated the nut yield and economic output value per unit area (670 m²), adjusted by the different LFRs, to determine the optimal walnut LFR.

Results

Regression Equations of LFR Effects on Pn, SMTR, and NDM

The results of regression analysis showed that the regression relationship between Pn/SMTR/NDM and LFR could be reflected by linear functions ($y = ax + b$), quadratic functions ($y = ax^2 + bx + c$), and cubic functions ($y = ax^3 + bx^2 + cx + d$). However, the degrees of fit (R^2) of the effect relationships established using the cubic function were the highest, at

Table 1. Regression relationship between leaf-to-fruit ratio and Pn, SMTR, and NDW of *J. regia* ‘Xinxin2’ walnut

Dependent variable ^z	Functional relationship	Fitting degree (R ²)	Regression relationship
Pn	Linear function	0.163	Pn = 0.590LFR + 10.485
	Quadratic function	0.733	Pn = -0.791LFR ² + 4.608LFR + 7.066
	Cubic function	0.735	Pn = 0.040LFR ³ - 1.097LFR ² + 5.231LFR + 6.758
Sqrt SMRT	Linear function	0.192	Sqrt SMRT = 0.092LFR + 1.349
	Quadratic function	0.569	Sqrt SMRT = -0.093 LFR ² + 0.563LFR + 0.948
	Cubic function	0.713	Sqrt SMRT = 0.048LFR ³ - 0.462LFR ² + 1.314LFR + 0.578
NDM	Linear function	0.883	NDM = 1.961LFR + 6.984
	Quadratic function	0.918	NDM = -0.279LFR ² + 3.379LFR + 5.777
	Cubic function	0.922	NDM = 0.073LFR ³ - 0.842LFR ² + 4.525LFR + 5.211

^zPn represents net photosynthetic rate; SMRT represents specific mass transfer rate; NDM represents the nut dry mass.

Table 2. Residual test of the regression relationship between leaf fruit ratio and Pn, SMTR, and NDW of *J. regia* ‘Xinxin2’ walnut

Parameter evaluation	Pn ^z	Sqrt SMRT	NDM
fruit development			
Regression equations	Pn = 0.040LFR ³ - 1.097LFR ² + 5.231LFR + 6.758	Sqrt SMRT = 0.048LFR ³ - 0.462LFR ² + 1.314LFR + 0.578	NDM = 0.073LFR ³ - 0.842LFR ² + 4.525LFR + 5.211
Fittings (R ²)	0.735	0.713	0.922
Samples (n)	45	45	45
Regression equation significance level P value	0.000	0.000	0.000
δ^2	0.9705 ²	0.6344 ²	0.7515 ²
Normal distribution	$\chi^2 = 4.7727 < \chi^2_{0.1}(6)$	$\chi^2 = 3.1037 < \chi^2_{0.1}(6)$	$\chi^2 = 2.0941 < \chi^2_{0.1}(6)$
chi-square test of residuals	= 10.64 e - N(0, 0.9705 ²)	= 10.64 e - N(0, 0.6344 ²)	= 10.64 e - N(0, 0.7515 ²)
First-order autocorrelation test of residuals	DW = 1.399 ∈ [1.383, 1.666] $\alpha = 0.05$	DW = 1.557 ∈ [1.383, 1.666] $\alpha = 0.05$	DW = 1.625 ∈ [1.383, 1.666] $\alpha = 0.05$
Test for homogeneity of variance	W = 0.231 < F _{0.05} (14,30) = 2.04	W = 1.374 < F _{0.05} (14,30) = 2.04	W = 0.016 < F _{0.05} (14,30) = 2.04

^zPn represents net photosynthetic rate; SMRT represents specific mass transfer rate; NDM represents the nut dry mass.

0.735, 0.713, and 0.922, respectively, which indicated that the cubic equation could more accurately reflect the relationship between Pn/SMTR/NDM and LFR (Table 1).

Residual Analysis for the Regression Equations of LFR Effects on Pn, SMTR, and NDM

We analyzed the residuals e_{ij} ($i = 1, 2, 3, \dots, 15; j = 1, 2, \text{ and } 3$) of the effect equation established with LFR as the independent variable (x) and Pn, SMTR, and NDM as the dependent variables (y) (Table 2). The results showed that the χ^2 values of the normal distribution χ^2 test for the residuals of the regression equations regarding the LFR effects on Pn, SMTR, and NDM were 4.7727, 3.1037, and 2.0941, respectively. These values were all smaller than $\chi^2_{0.1}(6) = 10.64$, which suggested that the residuals e_{ij} were subject to a normal distribution, i.e., $e - N(0, 0.9705^2)$, $e - N(0, 0.6344^2)$, and $e - N(0, 0.7515^2)$, respectively. When the sample size was 45, the number of variables was 3, and the significance level was $\alpha = 0.05$, the DW values of the residual independence Durbin-Watson (DW) test were 1.399, 1.557, and 1.625, respectively. These values were all within the range of [1.383, 1.666], suggesting that the residuals were mutually independent without first-order autocorrelation. The W values of the residual homogeneity of variance Levene's (W) test were 0.231, 1.374, and 0.016, respectively. These values were all smaller than $F_{0.05}(14, 30) = 2.04$, which suggested that the residual variance was not significant and showed homogeneity of variance. The test results indicated that the effects of LFR on Pn, SMTR, and NDM could be accurately determined using the cubic function relationship.

Residual Analysis for the Regression Equations of LFR Effects on Yield

The regression analysis revealed that the degrees of fit (R^2) of the effect relationships established using the cubic function for the effects of LFR on Lngamma Yield were the highest, at 0.632 (Table 3). Residual analysis results (Table 4)

Table 3. Regression relationship between leaf-to-fruit ratio and Lngamma Yield of *J. regia* 'Xinxin2' walnut (n = 45)

Dependent variable	Functional relationship	Fitting degree (R^2)	Regression relationship
Lngamma Yield ^z	Linear function	0.163	Lngamma Yield = 0.510LFR + 3.478
	Quadratic function	0.598	Lngamma Yield = -0.567LFR ² + 3.274LFR + 6.947
	Cubic function	0.632	Lngamma Yield = 0.937LFR ³ - 7.923LFR ² + 17.350LFR + 2.576

^zYield represents nut yield of a single tree.

Table 4. Residual test of the regression relationship between leaf fruit ratio and Lngamma Yield of *J. regia* 'Xinxin2' walnut

Parameter evaluation fruit development	Lngamma Yield ^z
Regression equations	Lngamma Yield = 0.937LFR ³ - 7.923LFR ² + 17.350LFR + 2.576
Fittings (R^2)	0.632
Samples (n)	45
Regression equation significance level p value	0.021
δ^2	5.9178 ²
Normal distribution chi-square test of residuals	$\chi^2 = 7.6349 < \chi^2_{0.1}(6) = 10.64$ $e - N(0, 5.9178^2)$
First-order autocorrelation test of residuals	DW = 1.624 \in [1.383, 1.666] $\alpha = 0.05$
Test for homogeneity of variance	W = 1.07 $< F_{0.05}(14, 30) = 2.04$

^zYield represents nut yield of a single tree.

showed that the residuals of the regression relationship between LFR and Lngamma Yield effect were distributed normally, independent of each other, and showed homogeneity of variance.

Establishing and Solving the Objective Function of Comprehensive Decision-Making for LFR

To determine the optimal LFR of the girdled walnut shoot and maximize the comprehensive expected value of its effects on Pn, SMTR, NDM, and Yield, the linear combination of the equations with respect to the LFR effects on Pn, SMTR, NDM, and Yield served as the objective function:

$$\text{Max: } Z = 1.098\text{LFR}^3 - 10.324\text{LFR}^2 + 28.420\text{LFR} + 15.123 \tag{3}$$

The maximum solutions reached by single expected values for the effects of LFR on Pn, SMTR, NDM, and Yield (Table 5) were used as the constraints for the objective function: $1.50 \leq \text{LFR} \leq 5$ and the solution given by programming was $\text{LFR} = 2.02$.

Validity Test of Comprehensive Optimal LFR

The maximum solutions reached by the single expected values of the LFR effects on Pn, SMTR, NDM, and Yield (Table 5) ($\text{LFR} = 3.35$, $\text{LFR} = 2.13$, $\text{LFR} = 5.00$, and $\text{LFR} = 1.5$) and the maximum solution ($\text{LFR} = 2.02$) reached by the comprehensive expected value (objective function) were substituted back into the four effect regression equations,

Table 5. Optimal LFR of single-effect regression equation of *J. regia* ‘Xinxin2’ walnut

Item ^z	Single optimal LFR
Effect regression equation of net photosynthesis rate $\text{Pn} = 0.040\text{LFR}^3 - 1.097\text{LFR}^2 + 5.231\text{LFR} + 6.758$	3.35
Effect regression equation of specific mass transport rate $\text{Sqrt SMRT} = 0.048\text{LFR}^3 - 0.462\text{LFR}^2 + 1.314\text{LFR} + 0.578$	2.13
Effect regression equation of nut dry weight $\text{NDM} = 0.073\text{LFR}^3 - 0.842\text{LFR}^2 + 4.525\text{LFR} + 5.211$	5.00
Effect regression equation of nut yield of single tree $\text{Lngamma Yield} = 0.937\text{LFR}^3 - 7.923\text{LFR}^2 + 17.350\text{LFR} + 2.576$	1.50

^zPn represents net photosynthetic rate; SMRT represents specific mass transfer rate; NDM represents the nut dry mass; Yield represents nut yield of a single tree.

Table 6. Validity test of optimum leaf-to-fruit ratio of *J. regia* ‘Xinxin2’ walnut

Item ^z	Predicted value	
	Overall optimal value	Single optimal value
Pn effect	14.78	16.07
SMTR effect	1.74	1.75
NDM effect	11.52	15.91
Yield effect	12.93	13.90

^zPn represents net photosynthetic rate; SMRT represents specific mass transfer rate; NDM represents the nut dry mass; Yield represents nut yield of a single tree.

respectively. When LFR = 2.02, the predicted values of the different indicators were within the allowable range and not significantly different from the single optimal values (Table 6), which suggested that the solution given by the objective function and the constraints was valid.

Estimation of Walnut Yield and the Economic Output Value per Unit Area Based on LFR

An equation for walnut yield per unit area of girdled shoots under different LFRs was designed:

$$Y_i = A_i \times W_i \times N_i \times 450 \times 22 \quad (4)$$

where Y_i , A_i , W_i , and N_i were the same as the above formula, and 22 denotes the number of walnut trees per unit area (670 m²) at a row spacing of 5 × 6 m.

In terms of nut yield, we calculated the nut yield without leaf-to-fruit ratio manipulation according to the formula (4) above, and the nut yield of all the bearing shoots in a natural state was 210.82 kg. We also calculated the nut yield with the minimum threshold LFR = 2.02. We put LFR ≥ 2 into the formula (4) to calculate the nut yield, and tried to adjust LFR < 2 to 2 by removing the fruit. If the LFR could not be adjusted, it would not be put into the formula (4). Finally, we got the nut yield when the minimum threshold LFR = 2.02 was 171.50 kg. Compared with the nut yield per unit area of walnut trees with unadjusted LFRs, the nut mass per unit area adjusted by the minimum LFR threshold (LFR = 2.02) declined by 19.52% (Table 7).

Table 7. Prediction of nut yield per unit area of walnut based on leaf-to-fruit ratio of *J. regia* 'Xinxin2' walnut

LFR ^z	Nut dry weight (g)	Walnut yield without leaf-to-fruit ratio manipulation		Walnut yield with the minimum threshold LFR = 2.02	
		The proportion of bearing shoots with aL:bF in the total bearing shoots (%)	Yield of bearing shoots with aL:bF (g)	The proportion of bearing shoots with aL:bF in the total bearing shoots (%)	Yield of bearing shoots with aL:bF (g)
1L:1F	8.97	1.00	887.73	0.00	0.00
1L:2F	7.27	0.20	287.98	0.00	0.00
1L:3F	6.61	0.20	392.94	0.00	0.00
2L:1F	11.47	6.98	7930.84	21.04	23906.13
2L:2F	8.97	8.59	15251.25	0.00	0.00
2L:3F	7.89	5.01	11735.22	0.00	0.00
2L:4F	6.37	0.46	1324.69	0.00	0.00
3L:1F	13.17	10.61	13843.09	29.63	43658.88
3L:2F	9.35	14.96	30658.64	0.00	0.00
3L:3F	8.97	3.18	8468.97	0.00	0.00
3L:4F	6.76	0.88	2844.27	0.00	0.00
4L:1F	14.53	7.31	10501.47	7.31	10501.47
4L:2F	11.47	10.14	23042.60	23.96	46997.81
4L:3F	9.91	12.73	37473.80	0.00	0.00
4L:4F	7.97	1.09	3870.52	0.00	0.00
5L:1F	16.02	3.45	5470.74	3.45	5520.74
5L:2F	12.39	8.91	21878.10	4.76	15888.28

Table 7. Prediction of nut yield per unit area of walnut based on leaf-to-fruit ratio of *J. regia* 'Xinxin2' walnut (Continued)

LFR ^z	Nut dry weight (g)	Walnut yield without leaf-to-fruit ratio manipulation		Walnut yield with the minimum threshold LFR = 2.02	
		The proportion of bearing shoots with aL:bF in the total bearing shoots (%)	Yield of bearing shoots with aL:bF (g)	The proportion of bearing shoots with aL:bF in the total bearing shoots (%)	Yield of bearing shoots with aL:bF (g)
5L:3F	10.76	0.00	0.00	3.15	10066.04
5L:4F	8.70	0.17	652.61	0.00	0.00
6L:1F	18.11	0.81	1428.75	0.81	1428.75
6L:2F	13.17	1.86	4853.56	1.86	4853.56
6L:3F	11.47	1.35	4601.70	1.42	4840.31
6L:4F	10.35	0.07	286.91	0.00	0.00
7L:1F	21.26	0.16	327.37	0.16	327.37
7L:2F	13.86	0.30	823.51	0.30	823.51
7L:3F	12.10	0.26	934.87	0.26	934.87
7L:4F	10.94	0.07	303.32	0.07	343.32
8L:2F	14.53	0.23	660.83	0.23	660.83
8L:4F	11.47	0.11	499.94	0.11	499.94
10L:2F	16.02	0.08	252.03	0.08	252.03
Total		100	210820.30	100	171503.80

^zLFR represents leaf-to-fruit ratio.

Table 8. Economic output value prediction of walnut unit area based on leaf and fruit ratio of *J. regia* 'Xinxin2' walnut

Forecast index	Walnut without leaf-to-fruit ratio manipulation	Walnut with the minimum threshold LFR = 2.02
Yield per unit area (kg)	210.82	171.50
Nut quality of Grade I (kg)	50.79	84.85
Nut quality of Grade II (kg)	76.84	86.65
Nut quality of Grade III (kg)	83.19	0.00
Economic output value (\$)	307.45	461.21
Labor cast (\$)	0.00	42.40

In terms of nut quality, we graded the walnuts with unadjusted LFR according to the classification standards of the national Walnut Quality Grades (GB/T20398—2006). For the total nut mass per unit area, the mass of Grade III nuts (nut mass ≤ 10 g) accounted for 39.46%, the mass of Grade II nuts ($10 \text{ g} < \text{nut mass} \leq 12 \text{ g}$) accounted for 36.45%, and the mass of Grade I nuts (nut mass $> 12 \text{ g}$) accounted for 24.09%. We also graded the nuts of walnut trees with the minimum threshold LFR = 2.02, and in the total nut mass per unit area, the mass of Grade III nuts accounted for 0%, the mass of Grade II nuts accounted for 50.52%, and the mass of Grade I nuts accounted for 49.48% (Table 8).

In the terms of economic benefits, based on a market survey, the purchase price of Grade III nuts was $1.56 \text{ \$} \cdot \text{kg}^{-1}$, the purchase price of Grade II nuts was $2.26 \text{ \$} \cdot \text{kg}^{-1}$, the purchase price of Special Grade and Grade I nuts was $3.11 \text{ \$} \cdot \text{kg}^{-1}$, and the labor cost adjusted based on the LFRs of 22 walnut trees was 42.40 \$ ($21.20 \text{ \$/person/d} \times 2 \text{ d}$). Compared with the economic output value per unit area of walnut trees with an unadjusted LFR, the economic output value per unit area of walnut trees adjusted by the minimum LFR threshold (LFR = 2.02) increased by 36.22% (Table 8).

Discussion

Assimilation and partitioning of carbohydrates play decisive roles in the growth and development of fruit trees and the formation of their economic yield (Li et al., 2007). The production efficiency of fruit trees as solar energy collectors depends on their receipt and transformation of light energy and their subsequent transport, storage, and utilization of carbohydrates (David, 1985). To increase the yield of fruit trees, this series of processes must be accelerated to the greatest extent during the cultivation and management of the trees. Carbohydrate partitioning is influenced by the supply capacity of the sources, the competitive capacity of the sinks, and the carbohydrate transport capacity of the phloem. In the cultivation and management practices of fruit trees, fruit growers may attempt to adjust the equilibrium of carbohydrate partitioning between vegetative growth and reproductive growth in fruit trees by artificially manipulating their source-sink relationships to guarantee fruit tree yields and fruit quality (Tuo, 2015). Therefore, it is necessary to determine an LFR range that is suitable for the growth and development of fruit trees based on the characteristics of carbohydrate assimilation and partitioning (transport and utilization) in walnut trees.

Our results demonstrated that an LFR of 2.02 in girdled fruit-bearing shoots resulted in high levels of leaf Pn, pedicel SMTR, NDM, and Yield. Therefore, the assimilation of carbohydrates in leaves, the transport of carbohydrates in the phloem of the pedicel, and the utilization of carbohydrates in sink fruits all reached high levels under an LFR of 2.02. In contrast, the carbohydrates reached high levels in only one or two of the three processes of assimilation, transport, and utilization under the other LFRs. Hence, the optimal LFR that can promote the assimilation and partitioning of carbohydrates in walnut trees was determined to be 2.02.

In our study, the optimal LFR was obtained by determining the regression equations with respect to the effects of LFR on Pn, SMTR, NDM, and Yield, followed by their linear combination. Previous studies mainly focused on the relationship between LFR and photosynthesis and fruit quality but rarely on how to determine the optimal LFR, and the determination of the optimal LFR was mainly based on the fruit quality. Determining the optimal LFR in this study was based on the assimilation, transport, and utilization of carbohydrates and is thus not only a more scientifically reasonable method of calculating the LFR, but is also expected to better reflect the essential role of LFR in regulating the yield of fruit trees and fruit quality.

Our results also showed that by performing the LFR adjustment of walnut trees using the maximum solution of the optimal LFR reached by the comprehensive expected value (LFR = 2.02) as the minimum criterion, and following the principle of retaining the leaves and removing the fruits, the yield per unit area was 19.52% lower than LFR unadjusted walnut trees (i.e., using the minimum LFR = 2.02), but the fruit quality was improved. The mass of nuts classified as Special Grade, Grade I, and Grade II accounted for 100% of the total nut yield per unit area, and the economic output value per unit area increased by 36.22%. This study indicates that improving fruit quality to produce Grade I and II nuts will increase economic output but decrease total yield in managing efficient LFR in nut production.

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