Agroforest Syst (2021) 95:1703–1718
https://doi.org/10.1007/s10457-021-00682-y

Water use efficiencies, economic tradeoffs, and portfolio optimizations of diversification farm systems in a desert oasis of Northwest China

Jie Xue · Caibian Huang · Jingjing Chang · Huaiwei Sun · Fanjiang Zeng · Jiaqiang Lei · Guojun Liu

Received: 21 February 2021 / Accepted: 3 September 2021 / Published online: 10 September 2021

Abstract Agroforestry system has been considered as an efficient solution to reconcile land use conflicts by tree-crop interaction and supplement. However, the water productivity, tradeoffs, and water-use portfolios of farm diversification in agroforestry combination with tree and/or crop monocultures are still missing, especially in arid water shortage regions. Based on portfolio theory and farmer perception, this study integrates experimental data, meteorological parameters, farmers questionnaire, and yields and prices to assess water use efficiencies, economic return-risk tradeoffs, and portfolio optimizations of diversification farm systems in Moyu oasis of Northwest China. Results show that all the planting layouts of agroforestry systems provide a better economic income than the combination in mixing agroforestry and monocultures in water-use tradeoffs using Sharp ratio. Moreover, allocating part farm area to the nut/fruit trees can increase economic water-use return compared to more crop cultivations, providing a good complement to farm income. The Sharpe ratios of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping for 23.70%, 15.71%, and 60.60% give the highest economic water-use return compared to the other planting layouts. Nevertheless, according to the minimum risk portfolio and risk-averse farmers' preference, the combination of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping and monocultures of jujube and apricot (the ratios of 32.01%, 27.63%, 8.11%, 9.81 and 22.45%) is recommended to use for planting layout in the study area. It is concluded that the combination with nut/fruit-crop agroforestry and sole nut/fruit tree is a financially efficient diversification strategy to improve the water

J. Xue (✉) · C. Huang · F. Zeng · J. Lei · G. Liu
State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
e-mail: xuejie11@mails.ucas.ac.cn

J. Xue · C. Huang · F. Zeng · J. Lei · G. Liu
Cele National Station of Observation and Research for Desert-Grassland Ecosystems, Cele 848300, Xinjiang, China

J. Xue · C. Huang · F. Zeng · J. Lei · G. Liu
University of Chinese Academy of Sciences, Beijing 100049, China

J. Chang
College of Resource and Environment Sciences, Xinjiang University, Urumqi 830046, China

H. Sun (✉)
School of hydropower and information engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China
e-mail: huaiweisun@whu.edu.cn

use efficiency and economic tradeoffs in arid water shortage regions.

Keywords Agroforestry system · Land use diversification · Portfolio theory · Sharp ratio · Water equivalent ratio · Water use efficiency

Introduction

The increase in food production is essential for satisfying the requirement of world population growth of Sustainable Development Goals (e.g. target 1and 2), needing to take full advantage of land and water resources (Jancsovszka 2016). This appeals for the development of sustainable land and water use that needs to take into account high yields and resources use efficiencies while overcoming adverse environmental influences (Paul et al. 2017).

With climatic variability and market uncertainties, the land-use diversification of agricultural systems has been considered as an important development strategy to solve the risks resulting from the single planting (Anton et al. 2012; Castro et al. 2015). In practice, the farm level monocultures of trees or crops and agroforestry combining tree and crop are two key options to diversify farm portfolios under limited land and water resources (Nair and Garrity 2012; Paul et al. 2017).

The farm level monoculture is a planting of crops or trees on respective parcels or compartments within a farm (Price 1995). The monoculture can effectively capture light, soil and water resources, increasing the productivity of individual components (Rao et al. 1997; Khasanah et al. 2015; Paul et al. 2017). Also, the agroforestry as a common land use system is a well-established practice for maximizing the food production and resource use efficiencies, securing farmer livelihood, reducing land degradation, and mitigating risks related to climate variation via supplementary tree-crop interactions (Smith et al. 1997, 2013; Bai et al. 2016; Duan et al. 2019).

It has reported that the agroforestry can provide an efficient strategy to improve land and water productivities by tree-crop intercropping on the same land parcel (Bai et al. 2016). The agroforestry development has largely applied worldwide, especially in semiarid and arid regions such as Africa, India, North America, Northwest China (Jamaludheen et al. 1997; van Asten et al. 2011; Fletcher et al. 2012; Zhang et al. 2015).

The agroforestry with tree-crop interactions compared to monocultures has basically confirmed increase land productivity using land equivalent ratio (LER) (Rao et al. 1997; Luedeling et al. 2016; Bai et al. 2016). The LER greater than 1 indicates more efficient land-use efficiency than monocultures (Willey and Rao 1980; Willey 1990). A great number of studies has pointed out that the tree-crop intercropping was an effective means in maximizing land use efficiency via LER metrics, such as 1.4 in oil palm-cocoa (Khasanah et al. 2020), 1.19 in pear-wheat (Meng and Zhang 2004), 1.24–1.45 in jujube tree-wheat (Zhang et al. 2013), 1.34 in apricot-peanut (Bai et al. 2016), 1.62 in walnut-wheat (Duan et al. 2019), and 2 in pear orchard-radish agroforestry system (Dupraz and Newman 1997; Smith et al. 2013). However, the comparatively few focuses are available on water use efficiency in the diversification farm systems with mixed farm level monoculture and agroforestry systems.

Undoubtedly, the water use efficiency is very important for meeting agricultural production around the world, especially in arid and semiarid regions. While the land use diversification strategies may reduce average per unit production costs and increase the stability of economic returns (Panzar and Willing 1988; Peter and Runge-Metzger 1994; Paul et al. 2017), an economic return and risk tradeoff of water use efficiency in the diversification farm systems is yet missing.

A well-recognized approach for solving the return-risk tradeoff and optimization of diversification strategy is modern portfolio theory (MPT) (Markowitz 1952, 2014), which has been considered as an efficient tool to select suitable combinations of land and water-use options under uncertainty (Castro et al. 2015; Djanibekov and Khamzina 2016). The MPT is to find an efficient frontier for maximizing economic return at the accepted risk level (Paul et al. 2017). In water shortage regions, the farmers' making decisions faces that what trees and/or crops combination between agroforestry and monocultures should they select to save water and to obtain high economic benefit with acceptable risk? In general, the farmers are universally risk-averse and more willing to accept stable revenues with low risk. Combining MPT and farmers'

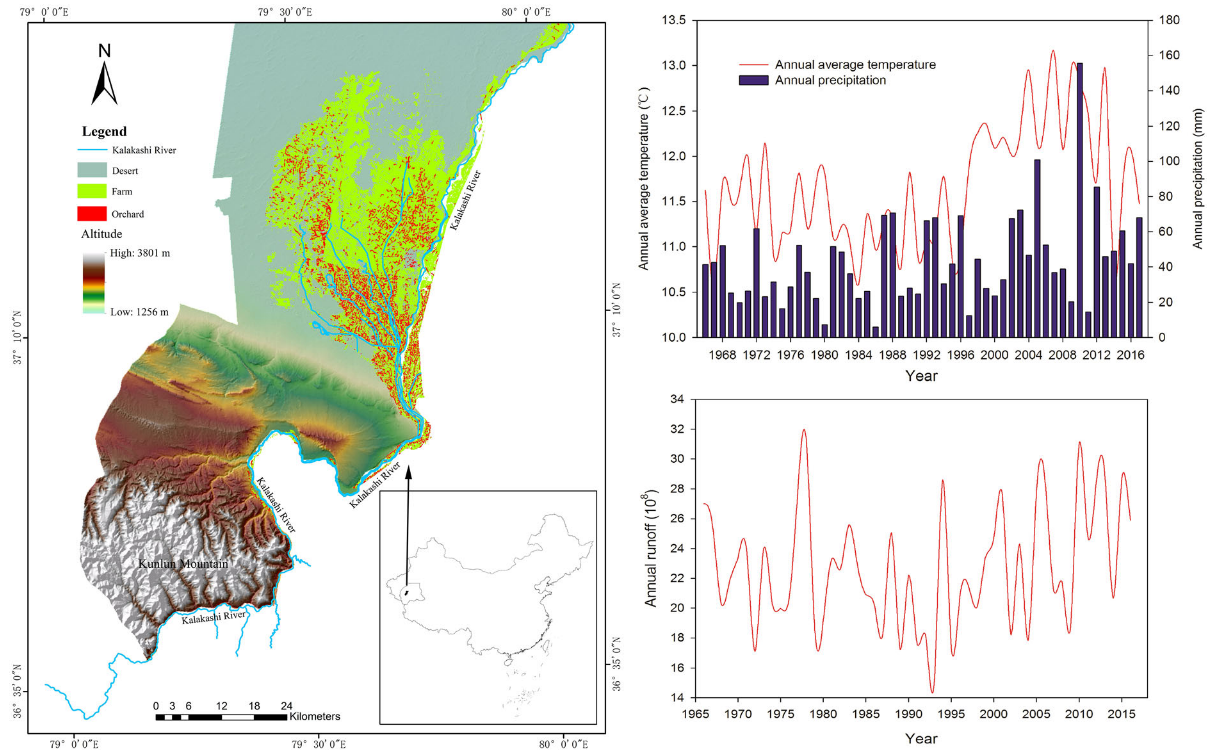

Fig. 1 location of the study area

willingness into water use assessment and portfolio optimization under uncertainty is, however, also lacking.

Based on the above issues, the objectives of this paper select the Moyu oasis in the south edge of Taklimakan desert of Northwest China as a case study: (a) to assess water use efficiency by tree/crop water requirement and water equivalent ratios in the diversification farm systems; (b) to quantify economic return-risk tradeoffs at given levels of risk using MPT; and (c) to conduct the water-use portfolio optimization of diversification farm systems under the farmers' preferences and willingness decision-making.

Materials and methods

Study area

The study area is conducted in Moyu oasis (37°00′–37°34′ N, 79°29′–80°05′ E), which is located between the downstream of Karakash River basin and the south edge of Taklimakan desert of Northwest China (Fig. 1). It belongs to the extreme arid area of warm temperate zone, with a relatively flat terrain and an elevation of 1256–1305 m. The annual maximum and minimum daily average temperature are 31.5 °C and − 8.2 °C, respectively. The annual average precipitation is only 34.7 mm, and the annual average pan evaporation reaches 2239 mm. The annual runoff of Karakash River is 22.77 ($10^8 m^3$). The temperature difference between day and night is large. The strong wind in spring leads to more numbers of floating dust days and often accompanied by sandstorms. Due to low precipitation and strong evaporation, the water supply in the Moyu oasis relies solely on river discharge, which originates in the alpine valley of the Kunlun Mountains, flowing through the Moyu oasis and ultimately discharging into the Taklimakan desert.

The contradiction between more people and less land and water is very prominent in Moyu oasis. This area is characterized by a conversion of oasis-desert ecotone into agriculture practices in the past 50 years (Huang et al. 2020). The salinized aeolian soil and water shortage limit the potential of agriculture development in the Moyu oasis, leading to high possibility of farm land abandonment (Kong et al. 2011). In turn, the regional sustainability puts larger pressure on agricultural structure adjustment and water-saving. The per capita arable land in this study area is 0.11 hm^2. The poverty alleviation and income improvement for farmers is main target of government appeal. The agricultural productions are the most key element of economic development in the region. Grain crops (wheat and maize), economic crop (alfalfa), fruit and nut trees (walnut, jujube, apricot), and agroforestry system (walnut/ jujube/apricot-wheat/maize) are the main planting layouts. The agroforestry with fruit and nut trees and crops intercropping is widely promoted as an economically viable land use option to conduct agricultural productions in mitigating water stress and preventing further desertification.

The study area is selected because water scarcities are particularly threatened, and thus, the water-use tradeoff and synthesis of diversification farm systems are urgently needed. The demonstration of the economic returns and portfolio optimization of different diversification strategies in Moyu oasis may contribute to other diversified landscapes in water scarcity environments.

Data sources

To assess the water-use efficiencies, the meteorological data was obtained from the Moyu weather station in the Moyu oasis for the period 1961–2017. For analyzing the impacts of field and price fluctuations on economic return-risk tradeoffs and portfolio optimization, the average maximum yields, prices and cultivated area of crops and nut/fruit trees were collected from Hotan Statistical Yearbooks recorded by the Government Office of Xinjiang Province (2007–2017).

To verify the land-use activities and farmers' willingness of planting layout, 524 face-to-face household questionnaires are surveyed in 2015 to quantify their opinions of land and water use in Moyu oasis. These households basically represented a total cultivated structure and planting layout. The questionnaire consisted of 20 questions including individual characteristic variables (i.e., age, gender, and education), family characteristics (i.e., population, household income, types of agricultural cultivation, irrigation), and living behavioral attitudes (i.e., preferences in cultivated crops for monocultures or agroforestry). The questionnaire information was then used to derive the historical proportions of all the farm types and yields in the study area. Here, this paper assumed that the plantation in small areas such as vegetation and herbs is negligible.

Methods

Tree/crop water requirement and water-use efficiency

According to the water requirement within the agriculture irrigation regions, the tree/crop water requirement (CWR) is assumed under adequate irrigation conditions as measured by maximum crop evapotranspiration (ET_m), which is calculated by (Allen et al. 1998; Steduto et al. 2012):

$$CWR = ET_m = k_c \times ET_0 \tag{1}$$

where ET_0 is reference crop evapotranspiration (mm), and k_c is the crop coefficient (dimensionless) during the plant growth periods. The ET_0 can be determined by the FAO Penman–Monteith model, which is given as (Allen et al. 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_0 is the reference evapotranspiration (mm/d), Δ is the slope of vapour pressure curve (kPa/°C), R_n is the net radiation at the crop surface (MJ/m^2d), G is the soil heat flux density (MJ/m^2d), γ is the psychometric constant (kPa/°C), T is the average monthly air temperature (°C), v_2 is the wind speed at 2 m height (m/s), and $e_s - e_a$ is the saturated vapor pressure deficit (kPa). In this study, according to Steduto et al. (2012) and previous experimental work (Huang et al. 2019; Liu et al. 2015; Liu et al. 2019; Jin et al. 2018), the tree/crop coefficients (kc) of various crops during the different growth periods are determined in Table 1. Moreover, the water consumption of tree-crop intercropping is obtained from previous experimental results and household questionnaires.

The tree/crop water use efficiency (WUE) in this study is given as tree/crop yield (Y) per CWR (Liu et al. 2020):

$$WUE = Y/CWR \tag{3}$$

The water-use efficiency of economics (WUE_e) is calculated as (He et al. 2012):

$$WUE_e = Y \cdot P/CWR \tag{4}$$

where P is the price of crops or nut/fruit trees.

Land and water equivalent ratios

Land equivalent ratio (LER) is used to evaluate land-use efficiency of agroforestry (Rao and Willey 1980). The LER is described as the total amount of intercropped tree and crop yields in an agroforestry system compared to the single tree and crop yields on a unit area (Bai et al. 2016):

$$LER = LER_a + LER_b = \frac{Y_{\text{int},a}}{Y_{mono,a}} + \frac{Y_{\text{int},b}}{Y_{mono,b}} \tag{5}$$

where LER_a and $LER_b$are the partial LER for tree (walnut) and for crops (wheat or corn), respectively. $Y_{int,a}$ and $Y_{int,b}$ are the yields of tree (walnut) and crops (wheat or corn) in tree-crop mixture, and $Y_{mono,a}$ and $Y_{mono,b}$ are the yields in monocultures tree (walnut) and crops (wheat or corn). When the LER is less than 1, an agroforestry system has lower land use efficiency than the single tree or crop. When the LER is equal to 1, there is no land-use advantage in the agroforestry system. When the LER is greater than 1, the agroforestry system has land productivity advantage, implying that producing the same yields in the monocultures tree and crop need more land compared to agroforestry system.

To express the water-use advantage of the tree-crop intercropping system, the water equivalent ratio (WER) as a metric is expressed by analogy with LER, which represents the amount of water in monocultures to reach the same yield with that in intercropping system (Mao et al. 2012):

$$\begin{aligned} WER = WER_a + WER_b &= \frac{Y_{\text{int},a}/WU_{int}}{Y_{mono,a}/WU_{mono,a}} + \frac{Y_{\text{int},b}/WU_{int}}{Y_{mono,b}/WU_{mono,b}} \\ &= \frac{WUE_{int,a}}{WUE_{mono,a}} + \frac{WUE_{int,b}}{WUE_{mono,b}} \end{aligned} \tag{6}$$

where WER_a and $WER_b$are the partial WERs of tree (walnut) and for crops (wheat or corn), respectively. WU_{int} is the actual evapotranspiration of whole tree-crop intercropping systems. $WU_{mono,a}$ and $WU_{mono,b}$ are actual evapotranspiration of tree (walnut) and crops (wheat or corn) in monocultures. $WUE_{mono,a}$ and $WUE_{mono,b}$ are the water-use efficiencies of tree (walnut) and crops (wheat or corn) in monocultures, while $WUE_{int,a}$ and $WUE_{int,b}$ are the water-use efficiencies of tree (walnut) and crops (wheat or corn) in tree-crop intercropping system. Analogous to LER, WER < 1 stands for water use disadvantage in tree-crop intercropping system, while WER > 1 indicates water use advantage in intercropping. The WER = 1 refers to the equal effects in monoculture and intercropping system.

Table 1 Tree/crop coefficients (k_c) with respect to various Tree/crop during the different growth periods

Month	Crop coefficients (k_c)					
	Wheat	Maize	Walnut	Jujube	Apricot	Alfalfa
January	0.21	0	0	0	0	0
February	0.21	0	0	0	0	0
March	0.86	0	0.80	0.85	0.75	0.08
April	1.14	0	0.85	0.95	0.85	0.50
May	1.00	0	0.90	1.05	0.90	0.50
June	0.65	0.72	0.95	1.15	1.10	0.62
July	0	0.84	0.95	1.15	1.10	0.80
August	0	1.02	0.95	1.15	1.10	0.70
September	0	1.08	0.90	1.10	0.90	0.45
October	0.55	0	0.80	0.90	0.85	0.10
November	0.58	0	0.85	0.85	0.80	0.08
December	0.52	0	0	0	0	0

Modern portfolio theory and water-use risk scenarios

The modern portfolio theory (MPT), proposed by Markovitz (1952, 2010, 2014) has been used to assess the risks of diversification in land-use allocation (Castro et al. 2015; Ocboa M, et al. 2016; Paul et al. 2017). This study applies the MPT to explore the economic water-use returns and risks of portfolios from the different sets of land use options in the diversification farm systems.

According to the MPT and basic theory of land allocation (Knoke et al. 2013), the expected economic water-use return of portfolio selection $E(r_p)$ of two or more different land-use strategies i, is determined by the weighted (w_i) sum of individual expected economic water-use returns $E(r_i)$:

$$E(r_p) = \sum_{i=1}^{n} w_i E(r_i) \tag{7}$$

where weights w_i sum is equal to 1. $E(r_i)$ is expected economic water-use return of different tree and crop planting layouts.

The economic water-use returns of land use strategies i for monocultures of crops and/or trees or agroforestry layouts are given by (Paul et al. 2017):

$$E(r_i) = \sum_{t=0}^{T} \frac{Y_{i,t} \cdot p_{i,t}}{(1+r)^t} \cdot \frac{(1+r)^T r}{(1+r)^T - 1} \tag{8}$$

where the economic water-use benefit of each year t is determined by WUE per hectare Y multiplied by the price P at a discount rate r (0.05) during the whole study period T of 11 years.

The portfolio risk in the MPT is described by the standard deviation (σ_p) of the expected economic water-use return, which is calculated by:

$$\sigma_p^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \mathrm{cov}(r_i, r_j) = \sum_{i=1}^{n} w_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} w_i w_j \rho_{ij} \sigma_i \sigma_j \tag{9}$$

where $\mathrm{cov}(r_i, r_j)$ and ρ_{ij} indicate the covariances and correlation coefficient between trees and crops. The value ρ_{ij}, σ_i and σ_j are calculated using a frequency distribution of expected return of each land-use strategy, which is simulated by Monte Carlo with 5000 time runs.

Portfolio optimization considering farmers' willingness

To express the profitability of a given portfolio exceeding economic water-use return from an associated level of risk, the Sharpe ratio (S_p) is used to assess the tradeoffs between returns and risks and to determine the optimum land-use options (Ocboa M, et al. 2016). The S_p is calculated as the ratio of the exceeding expected return of the portfolio to the standard deviation:

$$S_p = \frac{E(r_p) - R_f}{\sigma_p} \tag{10}$$

where R_f is the risk-free interest rate (0.05).

In practice, the willingness of the farmers who are the actual users of the farmlands will strongly influence the land use options with regardless of water consumption. In this work, the farmers' willingness is coupled into the portfolio optimizations, providing their perspectives and participations. Instead of giving a perfect assertion of expected planting layouts and economic benefits for the future, this paper attempts to show more preferable agricultural productions and offer recommendations in diversification farm systems for improving actual water use under farmer participation.

Results

Land and water use ratios in tree-crop intercropping

The land equivalent ratios in walnut/wheat and walnut/maize agroforestry systems show a fluctuation change (Fig. 2a). The LERs in walnut/wheat intercropping range from 1.61 to 1.76, but those in walnut/maize intercropping 1.66 to 1.74. Thus, there is a substantial land use advantage via mixing crops into trees. In a whole, the walnut/maize agroforestry has a significantly higher LER (average 1.71) compared to LER of the walnut/wheat intercropping (average 1.69). However, due to the climatic variability and different planting layout, the LERs in walnut/wheat intercropping are higher than those in walnut/maize agroforestry in the year of 2010 and 2013.

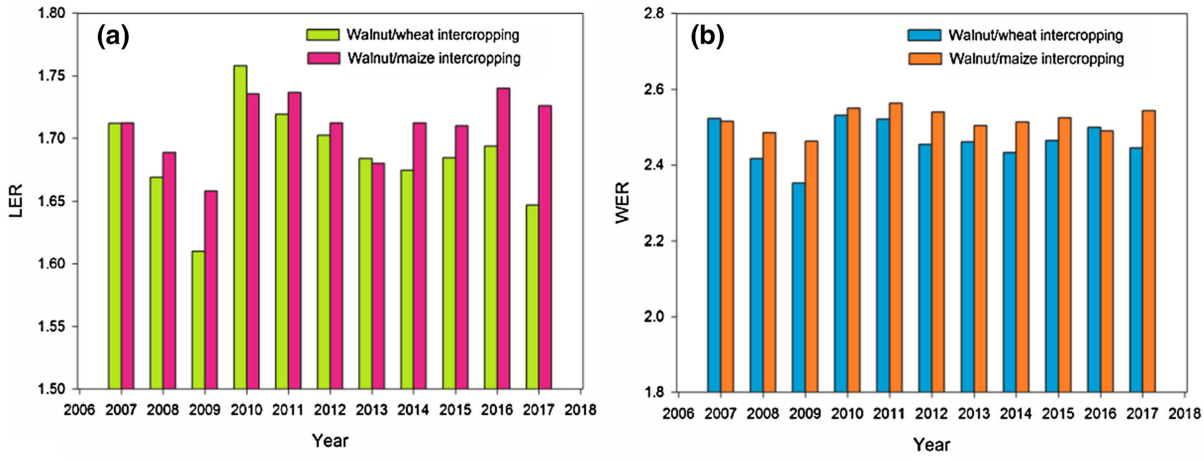

Fig. 2 Variations of LER and WER for the walnut/wheat and walnut/maize in the Moyu oasis

Figure 2b illustrates the WER variations in walnut/wheat and walnut/maize agroforestry systems during 2007–2017. Unlike LER, the water equivalent ratios in the tree-crop intercropping systems indicate a relatively small fluctuation. The WERs of walnut/wheat intercropping range from 2.35 to 2.53, but those in walnut/maize intercropping 2.46 to 2.56. The walnut/maize agroforestry has a significantly higher WER (average 2.52) than that of the walnut/wheat intercropping (average 2.46). In general, the WER values of walnut/wheat and walnut/maize agroforestry systems mean substantial water use advantages at the farm level.

Differences in water uses and productivities between tree-crop intercropping and monocultures

The walnut/wheat and walnut/maize agroforestry systems show significant water use efficiencies, which need less water than the sole crops and tree during 2007–2017 (Fig. 3a and b). The WUE of walnut/maize intercropping is 75% of the total sole tree and crop's, whereas the WUE in walnut/wheat agroforestry reaches 78% of the total sole tree and crop's. Compared to walnut/wheat intercropping, walnut/maize intercropping has higher average WUE (6.07 $\mathrm{kg/mm \bullet hm^2}$). With the impacts of climate change and yields, the WUEs in tree-crop intercropping and monocultures are characterized by a relatively stationary variation between 2007 and 2017, except that apricot's, shown in Fig. 3e. Overall, the WUEs of crops (wheat and maize) in agroforestry and monocultures are obviously higher than those of the nut fruit trees (walnut, jujube, and apricot).

Owing to the yield and/or market price fluctuations in some years, the WUE_e over time have a greater variability. Figure 3c and d indicate the WUE_e in walnut/wheat and walnut/maize agroforestry and monocultures during 2007–2017. The WUE_e in walnut/wheat and walnut/maize agroforestry and monocultures illustrate an approximately exponential growth pattern annually. The WUE_e in walnut/maize intercropping is 80 % of the total sole tree and crop's, while the WUE_e in walnut/wheat agroforestry reaches 82% of the total sole tree and crop's. The walnut/maize intercropping has higher average WUE_e (0.8 $\mathrm{Yuan/mm \bullet hm^2}$) than walnut/wheat intercropping. According to different annual WUE_e in tree-crop intercropping and monocultures, the WUE_e of walnut in agroforestry and monocultures is obviously higher than those of the fruit trees and crops (Fig. 3f).

Economic water-water returns and risk of the multiple land uses

Figure 4 shows return-risk profiles of the different diversification farm strategies in agroforestry and monoculture portfolios. The economic return can be maximized at any given level of risk from efficient frontier of minimum risk portfolio. Thus, the combination of all the monocultures in wheat, maize, walnut, and walnut/wheat and walnut/maize intercropping represent a poorer land use strategy due to low economic water-water returns at a certain risk level

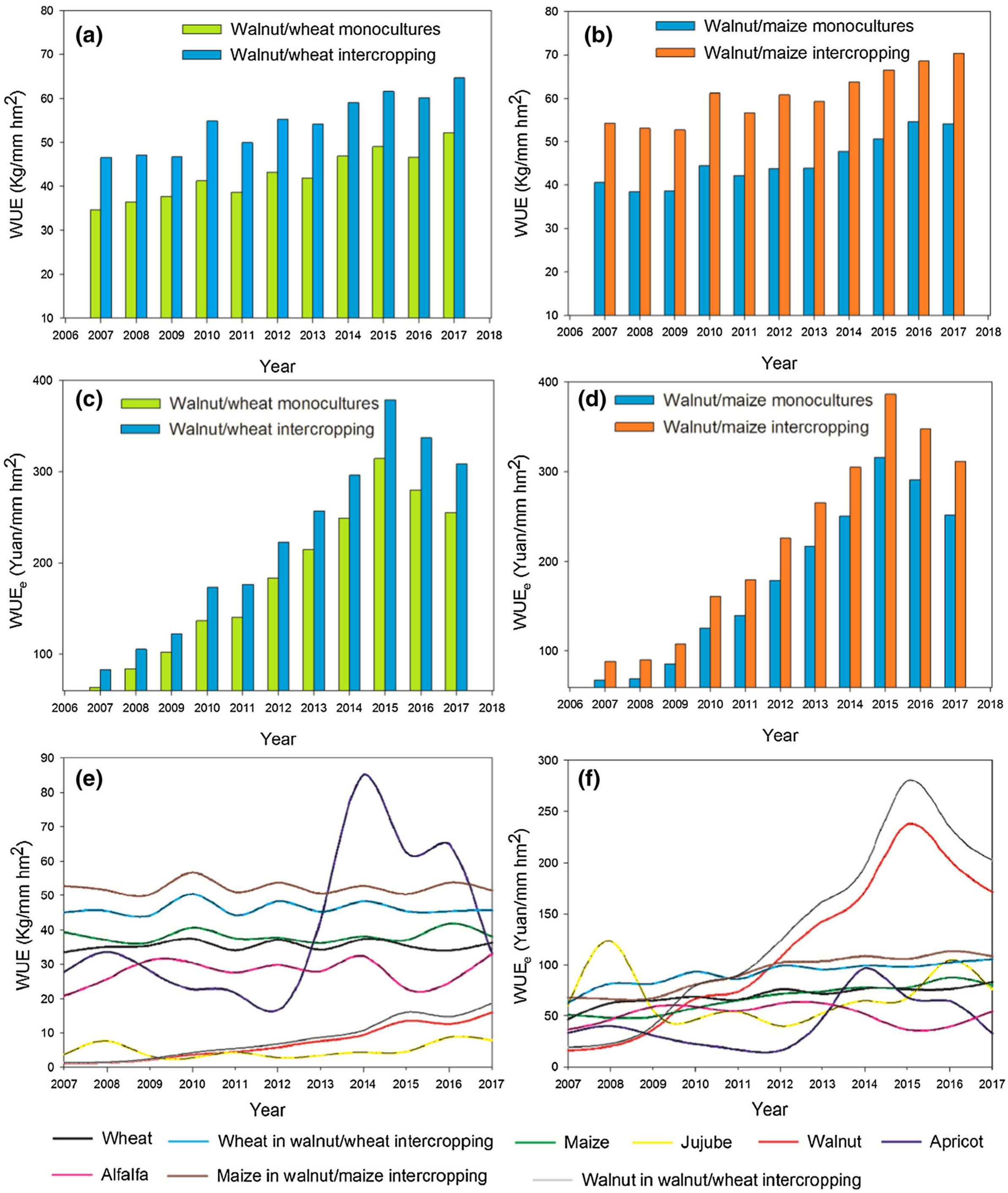

Fig. 3 Differences of WUE (**a**, **b** and **e**) and WUE_e (**c**, **d** and **f**) between intercropping and monocultures

(Fig. 4a and b). Compared to the above combination, the combination between walnut-wheat, walnut-maize intercropping and monocultures (walnut, wheat, maize) has higher economic water-water returns associated with a given higher risk level (see the red five-star mark and regular quadrilateral notation)

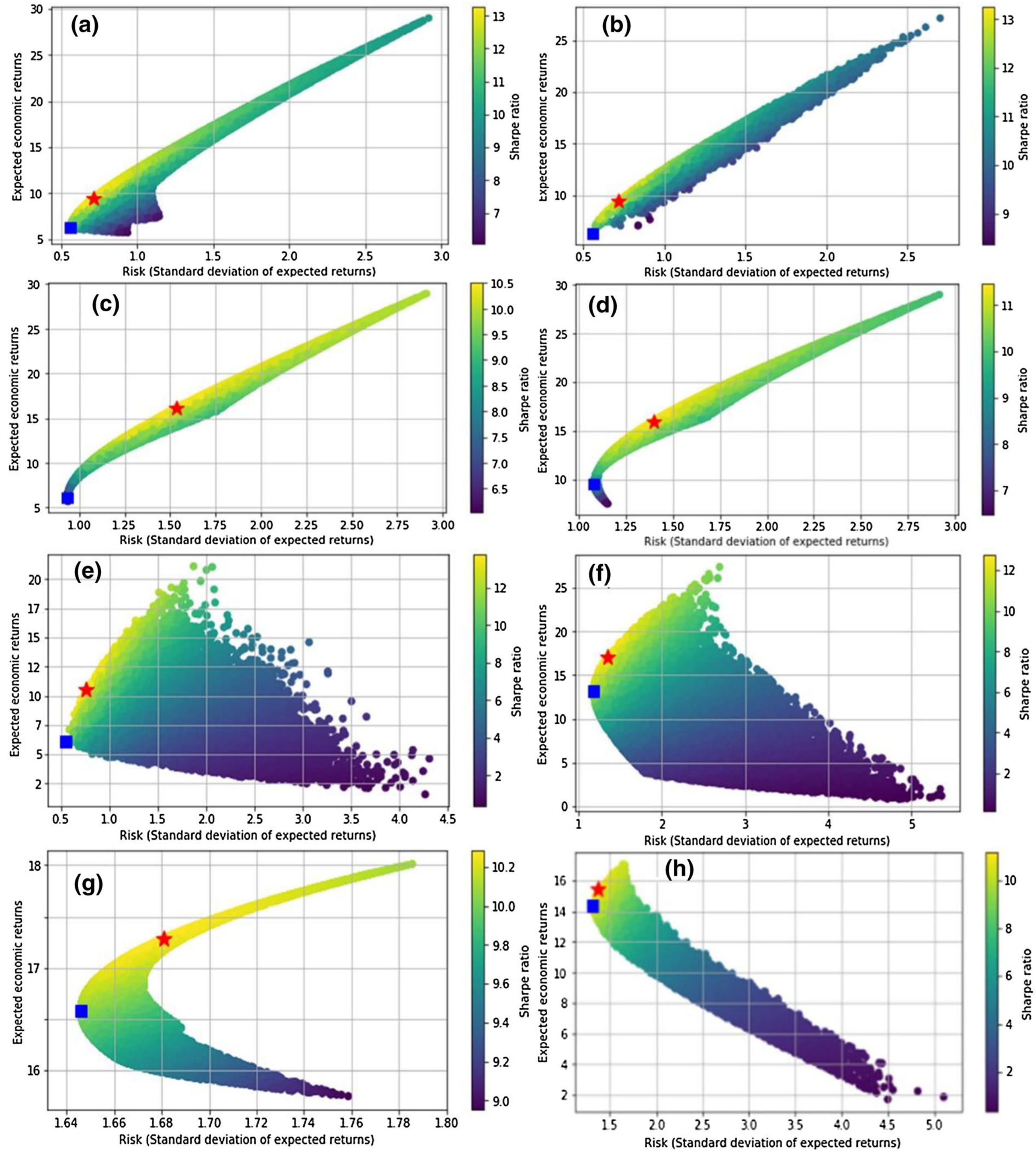

Fig. 4 Return-risk diagram of diversification farm systems in agroforestry and monocultures (the red five-star mark stands for Sharpe ratio, and regular quadrilateral notation refers to minimum risk portfolio)

(Fig. 4c and d). This reflects that the more the diversified planting layout is, the lower the return is under the main high fluctuations of walnut prices. However, the more diversified planting layout shows lower risky investment and return volatility.

Due to high market prices and economic benefits, the combination adding the jujube, apricot, and alfalfa demonstrates higher economic water-water returns at the high risks (Fig. 4e, f). This implies that allocating part farm area to the fruits can reduce economic risks

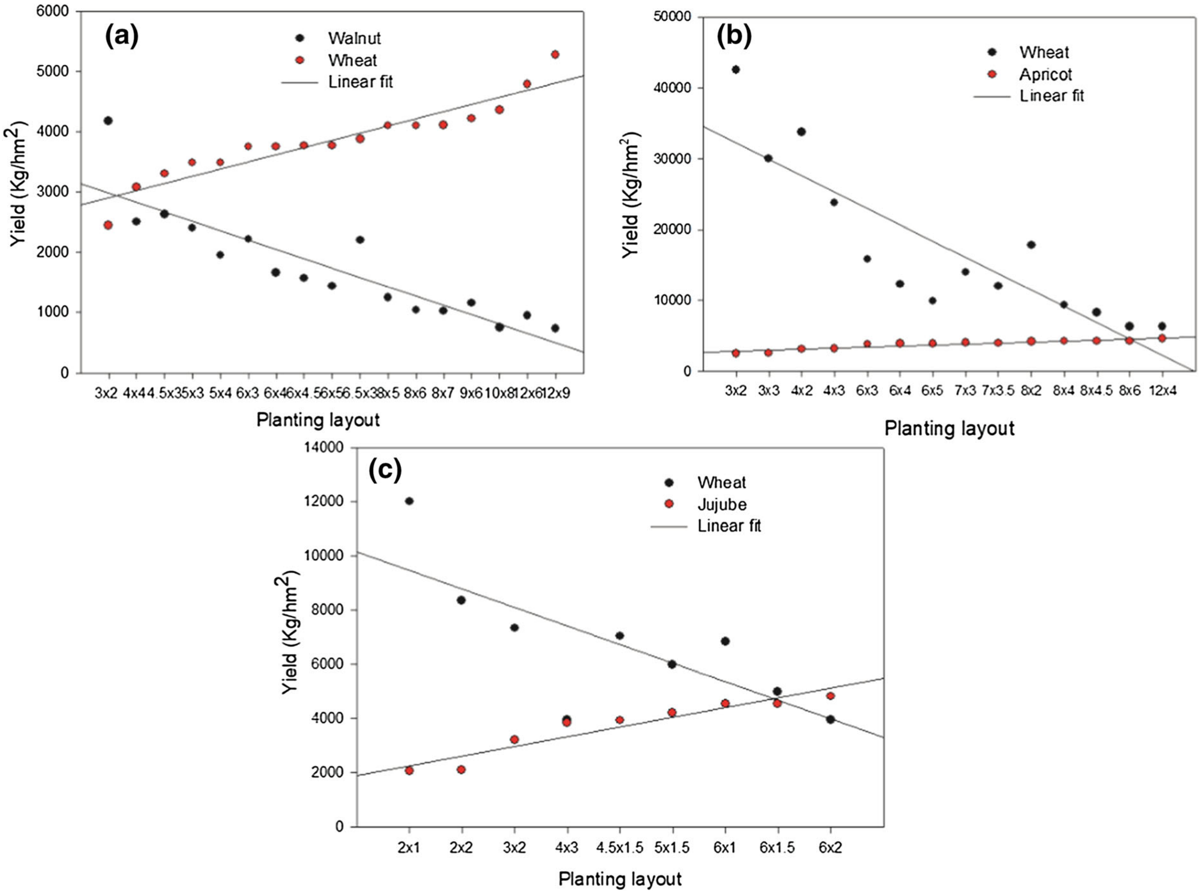

Fig. 5 Yields in walnut/wheat, apricot/wheat, and jujube/wheat intercropping

compared to more crop cultivations. Therefore, the fruits are a good complement to farm income.

In the total diversification farm systems, the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping give the highest economic water-water return compared to the other planting layouts at the same level (Fig. 4g). Also, the land use combination in walnut/wheat and walnut/maize intercropping shows a relatively higher return (Fig. 4h). According to the experimental results of Aimerjiang et al. (2016) and Wang et al. (2016), the different line spacings in walnut/wheat, apricot/wheat and jujube/wheat intercropping lead to different yields, WUE, and WUE_e under climate and price uncertainty (Figs. 5 and 6, and Fig. 7). Hence, excluding climate and market risk uncertainty, while the absolute risk level is comparably high, the whole planting layouts of agroforestry systems provide a better economic income than the combination in mixing agroforestry and monocultures in water-use tradeoff.

Portfolio optimization considering farmers preference

Based on water-use portfolios of the Sharpe ratio maximization (i.e., the farmers, who want to obtain the greatest excess return at tolerating one more unit risk, should choose the largest portfolio of Sharp ratio), it is demonstrated that agroforestry systems have the potential portfolios, when farmers prefer to accept certain risk levels. Especially, the combination of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping is recommended to buffer trade-offs between water use and economic benefits. This combination is financially attractive since it provides the highest expected economic returns at the same risk level. The Sharpe ratio of the portfolio can be as high as possible

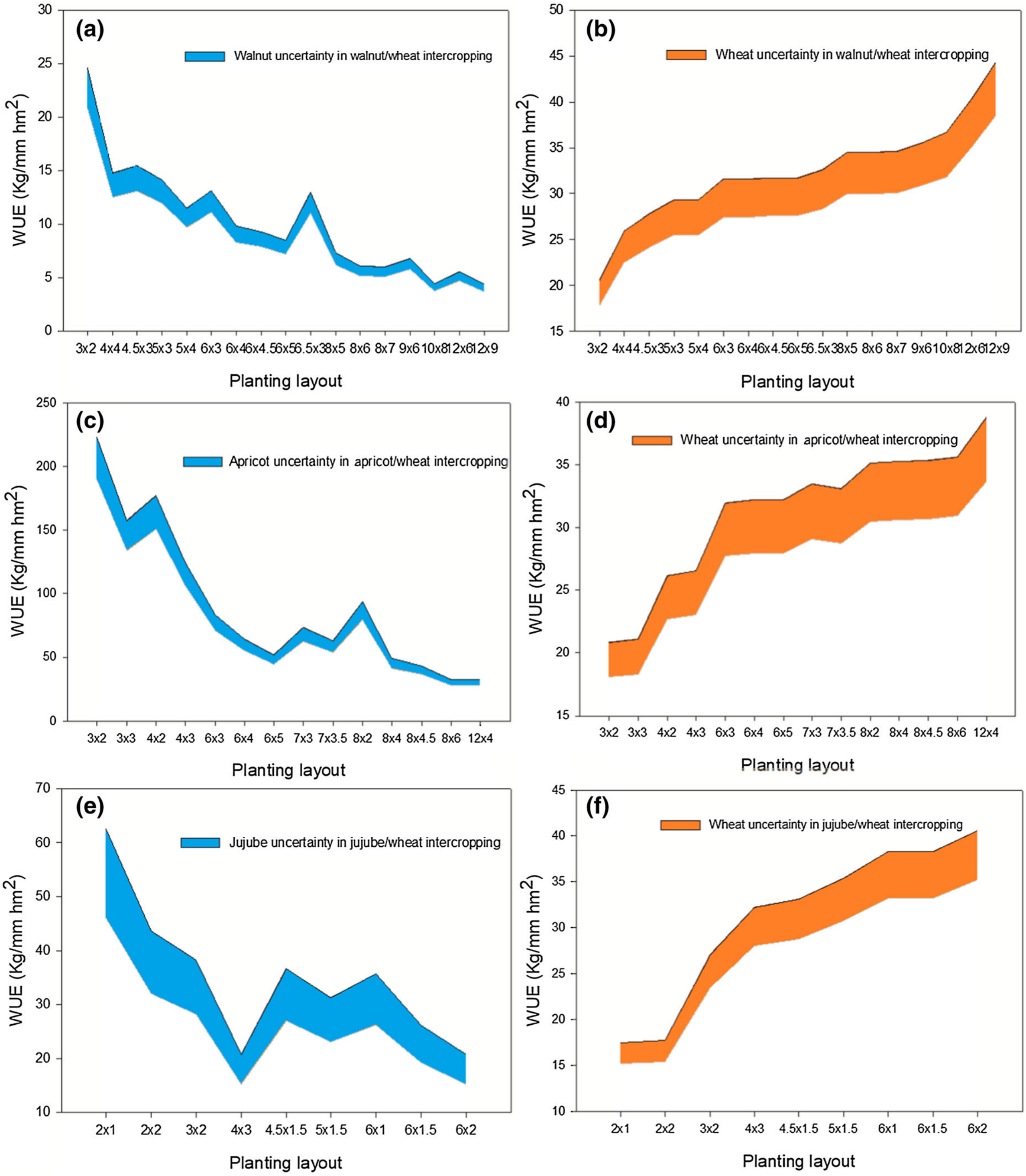

Fig. 6 *WUE* uncertainty in walnut/wheat, apricot/wheat, and jujube/wheat intercropping under climate change

10.28. Namely, the ratios of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping are 23.70%, 15.71 %, and 60.60 % under the portfolio's expected return 17.28 $\mathrm{Yuan/mm \cdot hm^2}$(Fig. 4g). Accepting the higher risk can be a key prerequisite in the potential adoption of farmers. Moreover, the combination in walnut/wheat and walnut/maize intercropping can thus offer alternative strategy due to relatively high Sharpe ratio.

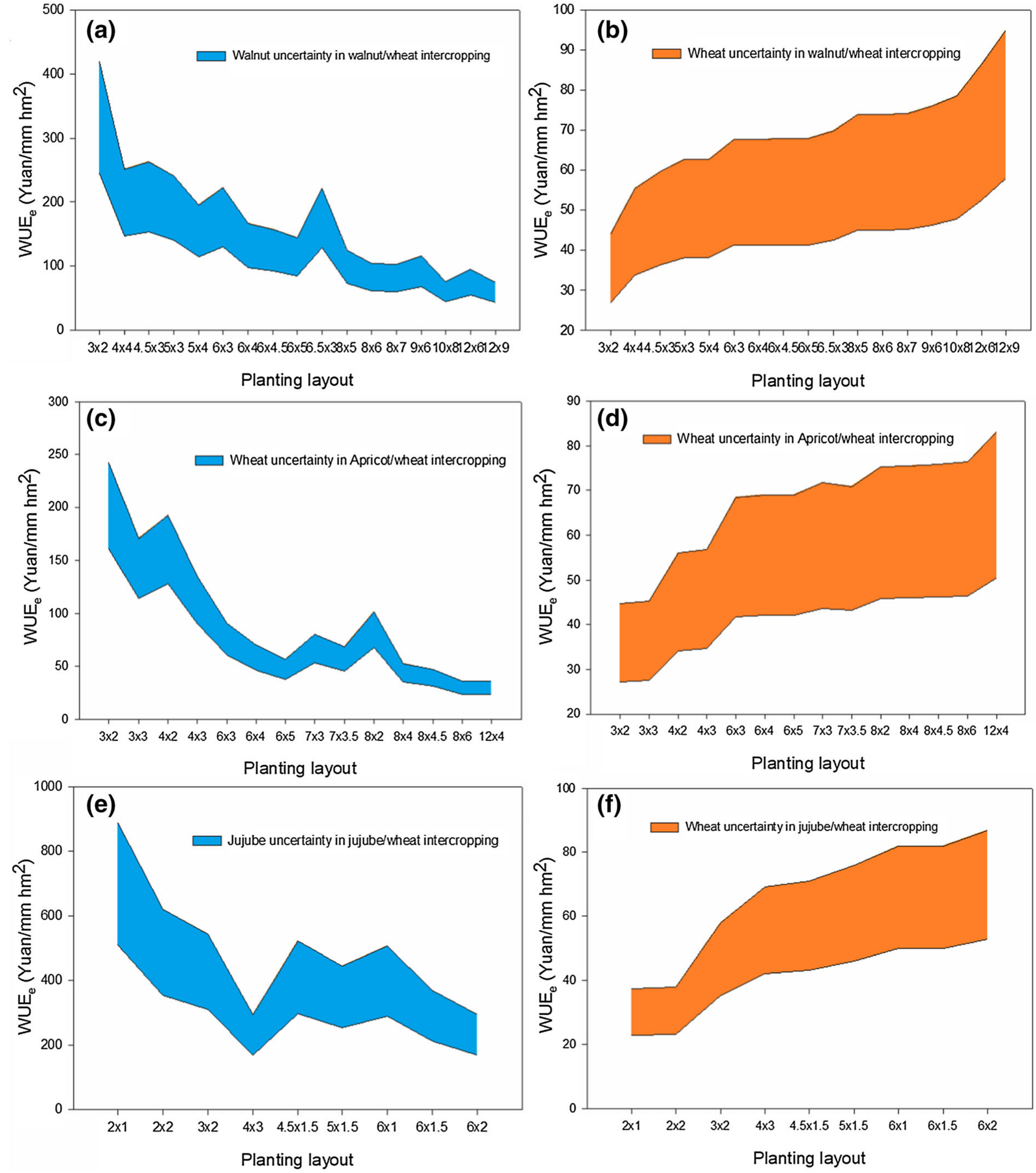

Fig. 7 *WUE_e* uncertainty in walnut/wheat, apricot/wheat, and jujube/wheat intercropping under market prices

In fact, the risk-averse farmers, who solely bear low levels of economic income variability, may opt to diversify farm systems with mixing agroforestry and monocultures. The farmers prefer to select the minimum risk portfolio, which may provide lower economic return volatility. To find the least investment risk, the MPT with the least variance should be selected to capture the optimal portfolio. According to the minimum risk portfolio and farmers' preference, the combination of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping and monocultures of jujube and apricot is recommended to use for planting layout. The proportions of planting layout are 32.01%, 27.63%, 8.11%, 9.81 and 22.45%, respectively. The portfolio has a standard deviation of 0.013, and a corresponding expected return of 14.34Yuan/mm • hm^2 (Fig. 4h).

Discussion

Importance of land-use diversification in avoiding unpredictable water-use portfolio risk

Land use diversification is very important in drylands due to extreme water shortage and price fluctuation (Ochoa M et al. 2016), which has threatened the land productivity and financial income of poor farmers (Sietz et al. 2011; Tadess et al. 2014). The findings of our study show that the agroforestry of nut/fruit tree-crop intercropping is a vital supplement for land-use diversification to promote water use efficiency, and to increase farmer income. The agroforestry of nut/fruit tree-crop intercropping economically is superior to monocultures of nut/fruit tree and crops in the water use efficiency of economics. This is consistent with the results of earlier experimental researches (He et al. 2012; Zhang et al. 2015; Bai et al. 2016; Duan et al. 2019), and modelling approach (Paul et al. 2017; et al. 2020). Moreover, the agroforestry can also be a key option to reduce evapotranspiration via canopy shading and to improve soil fertility (Holmgren et al. 2000; Quero et al. 2006; Glover et al. 2012; He et al. 2012). The main contribution of this paper not only analyzes productive and financial land- and water- use efficiency between agroforestry and monocultures, but also incorporates return-risk theory (MPT) into diversification farm trade-offs in long-term documentary time series. According the case study, the combination of nut/fruit tree-crop intercropping and fruit monocultures can increase economic water-use returns at the given risk levels, compared to other options of mixing nut/fruit trees and crops. Hence, a diversification of nut/fruit tree-crop intercropping provides a new planting layout perspective.

In line with previous researches, this work also illustrates that the farmers prefer to allocate land to lower risks in the diversification approach with regardless of water stress (e.g. Paul et al. 2017; Khasanah et al. 2015, 2020). Especially, the risk-averse farmers focus on the high economic and productive nut/fruit trees and crops under acceptable risk for short-term income. Moreover, this study supports the importance of land-use diversification incorporating nut/fruit trees and crops into farmland to coordinate economic water-use returns against climate risks. However, while higher economic returns in planting layout of nut/fruit trees, the pure agroforestry systems cannot replace the diversification combination with crop monocultures. Mixing agroforestry and monocultures of nut/fruit trees and crops is generally a preferable option in buffering water shortages and economic risks.

Meanwhile, the farmer's attitude to the risk and water-saving awareness is an important aspect in selecting a land-use option of diversification. The advantage of MPT doesn't describe an only best option or strategy, but instead describes a total set of options or strategies. The MPT can also help to choose prioritization scheme of land-use options by capturing the highest economic water-use benefit at the acceptable risks, and thus high probability for adoption under uncertainty (Ochoa et al. 2016; Paul et al. 2017). This paper demonstrates that considering farmer attitudes into MPT and decision-making provides an efficient means to design a sustainable diversification farm layout based on a participatory process.

The advantage of MPT is able easily to extend to assess a comprehensive set of options for forming efficient portfolios at different risk levels (Castro et al. 2015; Raes et al. 2014). The previous study has demonstrated that the MPT is an efficient means of land-use decisions via a farm-level portfolio optimization (Ochoa et al. 2016). In summary, this paper supports that land-use diversification with the combination between agroforestry and monocultures are important means for sustainable water productivity and expected economic water-use returns. Furthermore, coupling farmer's attitudes into portfolio theory can provide new perspectives to conduct trade-off and synergy between water use assessment and portfolio optimization under uncertain climatic and market price environment.

Limitations and further work of trade-off analysis between water use efficiencies and portfolio optimization of diversification farm systems under uncertainty

According to the combined results of the LER, WER, and return-risk theory, this paper assumes that water use assessment and decisions are pushed by economic benefits under climate and market uncertainty, as well as the farmer's viewpoint and preferences towards risk. Based on the case study at arid farm level, the main contribution of this work illustrates how land-use diversification options can be selected to improve water use efficiency under climate and price uncertainty. However, due to the short data verification to nut/fruit-crop interaction using documentary and empiric evaluation, the water use efficiency may be overestimated or underestimated in this study. The long-term statistical time series "covers up" effects of radiation, evapotranspiration, soil moisture, and root system on nut/fruit-crop interactions (Zhang et al. 2015; Bai et al. 2016; Duan et al. 2019).

In the water scarce regions, the interspecific water and heat relationships are crucial to the productivity of agroforestry systems (He et al. 2016). To further evaluate the comprehensive benefits, and to optimize the structure configuration of the diversification farm system, there is an urgent need to estimate water use efficiencies and portfolio optimization including agroforestry complex system coupling process of hydrothermal system, dynamic simulation model of root-cap structure, interspecific water and nutrient dynamic variation and its influencing mechanism at farm-scale level (Lusiana et al. 2012; He et al. 2016).

Considering the tendency of farmers in drylands to increase land use diversity to hedge the risks, the agroforestry systems may only constitute part farm area, and the diversification planting layout may form various combination of nut/fruit trees and crops for avoiding high risks (Baumgärtner and Quaas 2010). However, the related limitation of MPT method in trade-off analysis is the high data information requirement with accurate yield and price fluctuations (Paul et al. 2017). In fact, this information is seldom available because the most data is an aggregated and documentary level, which may not adequately capture water-use portfolio selection in uncertainty environment. It is an urgent need to use a robust approach to reduce the deficiency of the MPT with further improvements of the optimization algorithm (Knoke et al. 2015).

Impacts of other factors including overhead shading, nitrogen leaching, carbon sequestration, water competition in root system and carbon dioxide concentration within canopy on yields in diversified configuration of nut/fruit trees and crops, the competition between nut/fruit trees and crops in agroforestry system may largely reduce yields in small plots under uncertainty (Huang et al. 2011; Gan et al. 2015; Luedeling et al. 2016). Thus, developing a process-based model estimating nut/fruit tree and crop yields under different diversification strategies is provided an urgent chance to explore the water productivity of nut/fruit tree-crop interactions and their economic returns for an uncertain future.

Conclusions

Based on the case study at arid Moyu oasis of Northwest China, this paper assumes that water-use assessment and tradeoff are pushed by economic benefits under climate and market uncertainty, as well as the farmer's attitudes towards risk. This study illustrates how land-use diversification options can be selected to impact water use portfolios using the MPT approach considering farmers' willingness. Results show that the combination of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping is recommended to buffer trade-offs between water use and economic benefits using Sharp ratio. According to the minimum risk portfolio and farmers' preference, the combination of the walnut/wheat, walnut/maize, and walnut/alfalfa intercropping and monocultures of jujube and apricot is recommended to use for planting layout. These findings demonstrates that the combination with nut/fruit-crop agroforestry and sole nut/fruit tree is a financially efficient diversification strategy to improve the water use efficiency and economic tradeoffs in arid or extremely arid water shortage regions.

Acknowledgements This work was financially supported by the "Western Light" program of the Chinese Academy of Sciences (2017-XBQNXZ-B-016), the original innovation project of the basic frontier scientific research program, Chinese Academy of Sciences (ZDBS-LY-DQC031), the Natural Science Foundation of Xinjiang Uygur Autonomous Region (2021D01E01), the National Natural Science

Foundation of China (42071259, 51879110), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2019430).

References

Aimerjiang W, Wang JC, Ayixiemugli Y, Wu AQ, Xia JH, Turaysem Y (2016) Principle and technology of forest (fruit tree)-wheat intercropping in Xinjiang area. Jiangsu Agric. Sci. 44:72–77

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper No. 56. Rome, FAO

Anton J, Kimura S, Landkoski J, Cattaneo A (2012) A Comparative Study of Risk Management in Agriculture Under Climate Change. OECD Food, Agriculture and Fisheries Papers 58OECD Publishing, Paris

Bai W, Sun ZX, Zheng JM, Du GJ, Feng LS, Cai Q, Yang N, Feng C, Zhang Z, Evers JB, van der Werf W, Zhang LZ (2016) Mixing trees and crops increases land and water use efficiencies in a semi-arid area. Agr Water Manage 178:281–290

Baumgärtner S, Quaas MF (2010) Managing increasing environmental risks through agrobiodiversity and agrienvironmental policies. Agric Econ 41:483–496

Castro LM, Calvas B, Knoke T (2015) Ecuadorian banana farms should consider organic banana with low price risks in their land-use portfolios. PLoS ONE 10:e0120384

Djanibekov U, Khamzina A (2016) Stochastic economic assessment of afforestation on marginal land in irrigated farming system. Environ Resour Econ 63:95–117

Duan ZP, Gan YW, Wang BJ, Hao XD, Xu WL, Zhang W, Li LH (2019) Interspecific interaction alters root morphology in young walnut/wheat agroforestry systems in northwest China. Agroforest Syst 93:419–434

Dupraz C, Newman SM (1997) Temperate Agroforestry: The European Way. In: Gordon AM, Newman SM (eds) Temperate Agroforestry Systems. CAB International, Wallingford, pp 181–236

Fletcher EH III, Thetford M, Sharma J, Jose S (2012) Effect of root competition and shade on survival and growth of nine woody plant taxa within a pecan [Carya illinoinensis (Wangenh.) C. Koch] alley cropping system. Agroforest Syst 86:49–60

Gan YW, Li L, Li LH, Zhang W, Wang BJ (2015) Study of root distribution of walnut/wheat intercropping system in southern Xinjiang. Acta Agric Boreali-occidentalis Sinica 24:102–110

Glover JD, Reganold JP, Cox CM (2012) Agriculture: plant perennials to save Africa's soils. Nature 489:359–361

He CX, Meng P, Zhang JS, Gao J, Sun SJ (2012) Water use of walnut-wheat intercropping system based on stable carbon isotope technique in the low hilly area of North China. Acta Ecol Sin 32:2047–2055

He CX, Zheng N, Zhang JS, Meng P, Yuan WW (2016) Research advances on hydrological and thermal characteristics of agroforestry system. Chin J Agrometeorol 37:633–644

Holmgren M (2000) Combined effects of shade and drought on tulip poplar seedlings: trade-off in tolerance or facilitation? Oikos 90:67–78

Huang CB, Yan J, Ju JF, Yue J, Zeng FJ (2020) Dynamic changes of soil properties and their relationships with wheat yield in the new reclaimed farmland in the southern Tarim Basin. J Soil Water Conserv 34:245–252

Huang XQ, Dong YZ, Zhu XH, Chen H, Ye EJ (2011) Research of wheat yield in walnut-wheat intercropping system. Chin Agric Sci Bull 27:181–185

Jamaludheen V, Kumar BM, Wahid PA, Kamalam NV (1997) Root distribution pattern of the wild jack tree (Artocarpus hirsutus Lamk.) as studied by ^{32}P soil injection method. Agroforest Syst 35:293–336

Jancsovszka P (2016) Sustainable development goals (SDGS)

Jin Q (2018) Study on sap flow and production water footprint of primary economic forest in Cele oasis. University of Chinese Academy of Sciences, Beijing

Khasanah N, van Noordwijk M, Slingerland M, Sofiyudin M, Stomph D, Migeon AF, Hairiah K (2020) Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. Front Sustain Food Syst 3:122

Khasanah N, Perdana A, Rahmanullah A, Manurung G, Roshetko JM, Noordwijk MV (2015) Intercropping teak (tectona grandis) and maize (zea mays): bioeconomic trade-off analysis of agroforestry management practices in gunungkidul, west java. Agroforest Syst 89:1019–1033

Knoke T, Calvas B, Moreno SO, Onyekwelu JC, Griess VC (2013) Food production and climate protection—what abandoned lands can do to preserve natural forests. Glob Environ Chang 23:1064–1072

Knoke T, Paul C, Härtl F, Castro LM, Calvas B, Hildebrandt P (2015) Optimizing agricultural land-use portfolios with scarce data—a non-stochastic model. Ecol Econ 120:250–259

Kong WC, Wang RH, Wu MH (2011) Landscape pattern analysis and its ecological benefits in oasis plantation of Moyu county. Remote Sens Technol Appl 26:89–95

Liu GJ, Zeng FJ, Lei JQ, Lu Y, Guan JH (2015) Root distribution and growing of walnut trees and medicago sativa sodculture pattern. Arid Zone Research 32:504–508

Liu Y, Jin Q, Gui DW, Xue J, Sun HW, Yan D, Zeng FJ (2019) Characteristics of Sap Flow of Dwarf Red Jujube Trees and the Response to Environmental Factors in South Xinjiang. Arid Zone Research 36:1146–1152

Liu Y, Song W (2020) Modelling crop yield, water consumption, and water use efficiency for sustainable agroecosystem management. J Clean Prod 253:119940

Luedeling E, Kindt R, Huth NI, Koenig K (2014) Agroforestry systems in a changing climate-challenges in projecting future performance. Sustain Challeng 6:1–7

Luedeling E, Smethurst PJ, Baudron F, Bayala J, Huth NI, van Noordwijk M, Ong CK, Mulia R, Lusiana B, Muthuri C, Sinclair FL (2016) Field-scale modeling of tree–crop interactions: challenges and development needs. Agroforest Syst 142:51–69

Lusiana B, van Noordwijk M, Cadisch G (2012) Land sparing or sharing? Exploring livestock fodder options in combination with land use zoning and consequences for livelihoods and net carbon stocks using the FALLOW model. Agric Ecosyst Environ 159:145–160

Mao L, Zhang L, Li W, Werf WVD, Sun J, Spiertz H (2012) Yield advantage and water saving in maize/pea intercrop. Field Crops Res 138:11–20

Markowitz HM (1952) Portfolio selection. J Financ 7:77–91

Markowitz HM (2010) Portfolio theory: as I still see it. Annu Rev Financ Econ 2:1–23

Markowitz HM (2014) Mean–variance approximations to expected utility. Eur J Oper Res 234:346–355

Meng P, Zhang JS (2004) Effects of pear-wheat intercropping on water and land utilization efficiency. For Res 17:167–171

Nair PR, Garrity D (eds) (2012) Agroforestry - The Future of Global Land Use. Springer Netherlands

Ochoa MW, Santiago Paul C, Castro LM, Valle L, Knoke T (2016) Banning goats could exacerbate deforestation of the Ecuadorian dry forest – How the effectiveness of conservation payments is influenced by productive use options. Erdkunde 70:49–67

Panzar JC, Willig RD (1981) Economies of scope. Am Econ Rev 71:268–272

Paul C, Weber M, Knokeet T (2017) Agroforestry versus farm mosaic systems – Comparing land-use efficiency, economic returns and risks under climate change effects. Sci Total Environ 587–588:22–35

Peter G, Runge-Metzger A (1994) Monocropping, intercropping or crop rotation? An economic case study from the West African Guinea savannah with special reference to risk. Agroforest Syst 45:123–143

Price C (1995) Moderate discount rates and the competitive case for agroforestry. Agroforest Syst 32:53–61

Quero JL, Villar R, Maranón T, Zamora R (2006) Interactions of drought and shade effects on seedlings of four Quercus species: physiological and structural leaf responses. New Phytologist 2006, 170: 819–834

Raes L, Aguirre N, D'Haese M, van Huylenbroeck G (2014) Analysis of the cost-effectiveness for ecosystem service provision and rural income generation: a comparison of three different programs in Southern Ecuador. Environ Dev Sustain 16:471–498

Rao M, Nair P, Ong C (1997) Biophysical interactions in tropical agroforestry systems. Agrofor Syst 38:3–50

Rao MR, Willey RW (1980) Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea. Exp Agr 16:105–116

Sietz D, Lüdeke MKB, Walther C (2011) Categorisation of typical vulnerability patterns in global drylands. Special Issue on The Politics Policy of Carbon Capture Storage 21:431–440

Smith DM, Jarvis PG, Odongo JCW (1997) Sources of water used by trees and millet in Sahelian windbreak systems. J Hydrol 198:140–153

Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protectionof the environment: is temperate agroforestry the answer? Renew Agric Food Syst 28:80–92

Steduto P, Hsiao TC, Fereres E, Raes D (2012) Crop yield response to water. Food and Agriculture Organization of the United Nations

Tadess G, Algieri B, Kalkuhl M, Braun J (2014) Drivers and triggers of international food price spikes and volatility. Food Policy 47:117–128

van Asten PJA, Wairegi LWI, Mukasa D, Uringi NO (2011) Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. Agroforest Syst 104:326–334

Wang JC, Aimerjiang W, Ayixiemugli Y, Wu AQ, Xia JH, Zhang DH (2016) Analysis about wheat growth and yield formation in walnut/wheat intercropping system. Acta Agriculturae Boreali-occidentalis Sinica 25:1289–1296

Willey RW (1990) Resource use in intercropping systems. Agric Water Manag 17:215–231

Willey RW, Rao MR (1980) A competitive ratio for quantifying competition between intercrops. Ex Agric 16:117

Zhang W, Ahanbieke P, Wang B, Xu W, Li L, Christie P, Li L (2013) Rootdistribution and interactions in jujube tree/wheat agroforestry system. Agroforest Syst 87:929–939

Zhang W, Ahanbieke P, Wang BJ, Gan YW, Li LH, Christie P, Li L (2015) Temporal and spatial distribution of roots as affected by interspecific interactions in a young walnut/wheat alley cropping system in northwest China. Agroforest Syst 89:327–343