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# The use of water allocation efficiency in optimizing crop production in drylands using a fuzzy trading model

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## ABSTRACT

Considering the importance of agriculture in food security in arid and semiarid areas, it is absolutely necessary to apply the planning model based on different objectives. This study has been conducted to simulate the trading and non-trading policies in the Particle Swarm Optimization framework for estimating the optimal economic values of agricultural water in Jilin province, northeastern China. Fuzzy solutions have been also calculated by definition of the feasible domain for water availability and permits. A generalized extreme value function was incorporated into the problem to predict the rainfall amounts with a 25-year return period. The results showed that determining the agricultural pattern using a trading policy with the aim of benefiting from the water will reduce the water demand in the study area. The trading policy can lead to a more efficient allocation of released water and reduce water scarcity, but it can eliminate some plants from the cropping pattern by reducing the water level. As a result, trading policy can be effective in the short term, especially in drought conditions due to insufficient water supply.

**Key words:** food security, Particle Swarm Optimization, trading and non-trading plans, water resources management

## HIGHLIGHTS

- A model based on a fuzzy trading model with water and land constraints was developed.
- Two strategies of trading theory have been used for maximizing economic efficiency.

## INTRODUCTION

Water rights and water markets are increasingly important as cost-effective tools for the sustainable management of water resources (Lv *et al.* 2021, 2022). A transparent and sustainable water allocation system is essential to maintain the world's agricultural production and global food security (Tian *et al.* 2020; Cheng *et al.* 2022; Zhang *et al.* 2022). Rosegrant *et al.* (1995) and Zhao *et al.* (2022) reported that there is considerable evidence of flexibility in irrigation planning that increases the economic value of water. Therefore, tradable water rights markets can be effectively implemented with the appropriate design of water laws, institutions, and regulations (Liu & Yan 2022; Randeniya *et al.* 2022).

The economic, social, ecologic, and environmental benefits of water trading and the limitations of using market-based instruments for drought adaptation in Australia are assessed by Kiem (2013). The results confirmed that water trading has significant potential as a climate change adaptation strategy. In this regard, there are various uncertainties about the effects of water trade on the environment and agriculture. Zeng *et al.* (2014) introduced a cost-effective water trading policy under multiple uncertainties. For this purpose, they used an integrated optimization technique to deal with uncertainties expressed as probability distributions, discrete intervals, and fuzzy sets. The results of the study analyzed a number of policy scenarios with different levels of decreasing water licensing and trading ratios in China and provided insight into the trade-off between water trading and economic objectives.

Zeng *et al.* (2016) developed a probabilistic multistage trade-off planning method for planning water resource management under uncertainty. This method was able to reflect the dynamics in terms of water resource allocation decisions through transactions at discrete points. Monte Carlo simulation has been used to evaluate the probability distributions of the water trade

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ratio. The results of the amount of water trading, water allocation pattern and system profit under different possibilities showed that the water trading plan is an effective method for allocating limited water resources with maximum system profit in dry areas. In Iran, the effectiveness of water trade policy has been investigated as a solution for optimal use of dam reservoir water among farmers (Jansouz *et al.* 2017). Two water allocation programs under non-commercial and trading systems were designed with two-stage stochastic planning technique and uncertainties in the form of intervals and probability distributions. The results showed that the allocation of water under the commercial policy has been able to lead to the release of water and reduce the water shortage by maintaining the agricultural profit in non-commercial conditions.

Zheng *et al.* (2021) developed a systematic framework of water trading based on practices based on withdrawal permits in China. Water trading rules, trading systems in agriculture are evaluated for management implications. The suggestions presented confirmed that the use of market experiences in water allocation will contribute to food security in the future. Iftekhar & Fogarty (2022) investigated the impact of the groundwater trading process on the horticultural sector in Australia. An optimization simulation framework is developed based on detailed water allocation data to evaluate market performance. Optimization of supply and demand functions for water at the farm level was used at the individual scale. The market price for water was established through a two-way equal-price auction. The results showed that significant economic benefits have been made possible through the creation of a trading permit system. Furthermore, groundwater trading is able to reduce the reallocation of water to the most efficient producers by 14% but preserve the existing value of agricultural production in the region.

In recent years, the rapid liberalization of developing economies has led to the diversification and commercialization of agriculture. Current methods of water allocation tend to limit the flexibility of farmers to reallocate resources in response to changing incentives (Di *et al.* 2020; Liu *et al.* 2022). Modifying water allocation mechanisms is an effective step in agriculture. In the development of water allocation mechanisms, the technical, climatic, and economic characteristics of water resources are considered to create a balance between supply and demand (Islam *et al.* 2017). Based on this concept, in this article, an attempt has been made to develop an optimal system based on trading and non-trading policies to increase the economic value of water and water saving in drought conditions. In addition, the solutions of the problem are defined in an uncertain domain to reduce the risk of decision-making. This structure has been evaluated for 9 cultivated plants in a part of semiarid areas of Jilin Province in Northeast China.

## Simulation–optimization framework

The model developed to evaluate the impact of trading policy on water allocation is drawn as shown in Figure 1. The input data of the problem include water availability, water demand, and water permits. Each of these parameters has a specific definition that will be mentioned. The economic parameters that determine the value of water in the estimation of profit in agriculture are another part of the input information to the model (Lumbroso *et al.* 2014). In the first step, this information will be included in the structure designed for the non-trading policy in the form of fuzzy analysis. The output of the model is the non-trading of the main components of the water budget and the profit from the implementation of the policy. In the final step, the information obtained from the non-trading policy is transferred to the fuzzy trading model and the amount of water saved is calculated as a result of the proposed model.

## Non-trading policy

The proposed optimization model is developed based on the maximization or minimization of the objective function with the constraints applied from the trading or non-trading theory. In each iteration, two fuzzy limits of the response were obtained according to the following equations. According to the flowchart in Figure 1, the mathematical model of the non-trading policy is in the form of an optimization model in the form of Equations (1)–(5).

$$\text{Max } OF^{\pm} = \sum_{i=1}^{n} (B^{\pm} W^{\pm})_i - \sum_{i=1}^{n} \sum_{j=1}^{m} D_{ij}^{\pm} P_j C_i^{\pm} \tag{1}$$

$$\begin{cases} W_i^{\pm} - D_{ij}^{\pm} = \dfrac{G_i Q_j^{\pm}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i \geq Q_j^{\pm} \\ \sum_{i=1}^{n} (W_i^{\pm} - D_{ij}^{\pm}) \leq \dfrac{Q_j^{\pm}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i < Q_j^{\pm} \end{cases} \tag{2}$$

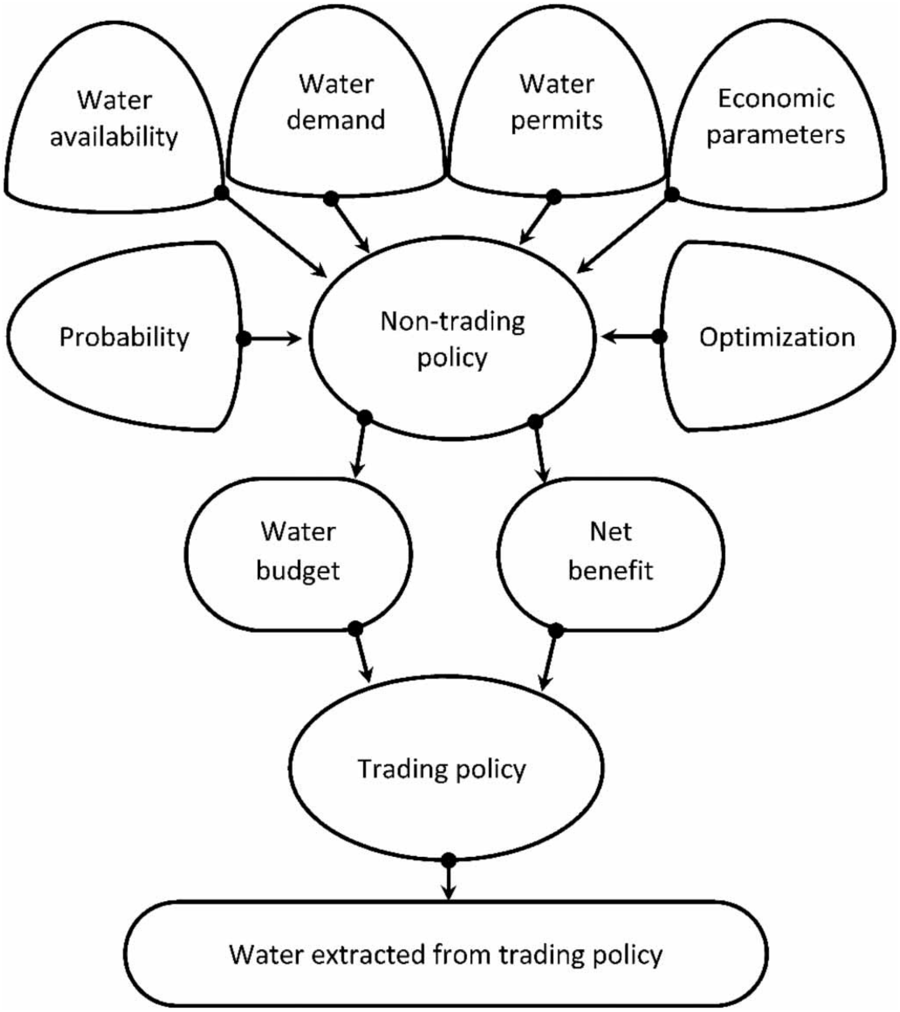

**Figure 1** | Simulation–optimization process to estimate the economic value of water.

$$L_i \leq W_i^{\pm} \leq G_i \tag{3}$$

$$0 \leq W_i^{\pm} - D_{ij}^{\pm} \leq U_i \tag{4}$$

$$0 \leq D_{ij}^{\pm} \tag{5}$$

where $OF$ is the objective function (maximization of the net benefit of the system) (Yuan), $B$ is the net benefit of each farmer (Yuan.m$^{-3}$), $W$ is the annual allocated water (m$^3$), $L$ is the minimum annual water demand (m$^3$), $G$ is the annual water permit (m$^3$), $U$ is the maximum annual water demand (m$^3$), Q is the total annual access to water of the system under probability $P_j$, $D$ is the annual water shortage (m$^3$) when the access to water of the system is equal to $Q$, and C is the cost of water supplement (Yuan.m$^{-3}$).

This model is the first stage of stochastic planning that considers the system without water trading according to the constraints of the model. Therefore, the objective function is subjected to:

Equation (2) reflects the water allocation plan in the non-trading policy. Because each farm has only the right to use its water permits. Furthermore, the total water access of the system is limited to the total water access of the system in the non-trading policy. Equation (3) in the non-trading policy states that the water consumption in each farm is limited to its water permit. Equation (4) indicates that the water consumption for each farm is less than or equal to the maximum water demand.

To determine the fuzzy limits of the model, it is necessary to estimate the lower and upper extreme values. Therefore, the upper and lower bounds are obtained by following equations, respectively.

$$
\begin{aligned}
&\text{Max } OF^{+} = \sum_{i=1}^{n}(B^{+}W^{+})_i - \sum_{i=1}^{n}\sum_{j=1}^{m} D_{ij}^{-}P_jC_i^{-}\\
&\text{s.t.}\\
&\begin{cases}
W_i^{+} - D_{ij}^{-} = \dfrac{G_iQ_j^{-}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i \geq Q_j^{+}\\
\sum_{i=1}^{n}(W_i^{+} - D_{ij}^{-}) \leq \dfrac{Q_j^{+}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i < Q_j^{+}
\end{cases}\\
&L_i \leq W_i^{+} \leq G_i\\
&0 \leq W_i^{+} - D_{ij}^{-} \leq U_i\\
&0 \leq D_{ij}^{-}
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
&\text{Max } OF_N^{-} = \sum_{i=1}^{n}(B^{-}W^{-})_i - \sum_{i=1}^{n}\sum_{j=1}^{m} D_{ij}^{+}P_jC_i^{+}\\
&\text{s.t.:}\\
&\begin{cases}
W_i^{-} - D_{ij}^{+} = \dfrac{G_iQ_j^{-}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i \geq Q_j^{-}\\
\sum_{i=1}^{n}(W_i^{-} - D_{ij}^{+}) \leq \dfrac{Q_j^{-}}{\sum_{=1}^{n} G_i} & \sum_{i=1}^{n} G_i < Q_j^{-}
\end{cases}\\
&L_i \leq W_i^{-} \leq G_i\\
&0 \leq W_i^{-} - D_{ij}^{+} \leq U_i\\
&0 \leq D_{ij}^{+}
\end{aligned}
\tag{7}
$$

### Trading policy

The trading policy in this article is to minimize the total annual water consumption of the system (Equation (8)).

$$
\text{Min } OF_T^{\pm} = \sum_{i=1}^{n}(W^{\pm})_i - \sum_{j=1}^{m} P_jD_{ij}^{\pm} \tag{8}
$$

S.t.

$$
\left(\sum_{i=1}^{n}(B^{\pm}W^{\pm})_i - \sum_{i=1}^{n}\sum_{j=1}^{m} D_{ij}^{\pm}P_jC_i^{\pm}\right) \geq OF_N^{\pm} \tag{9}
$$

$$\sum_{i=1}^{n} W_i^{\pm} \leq \sum_{i=1}^{n} G_i \tag{10}$$

$$\sum_{i=1}^{n} (W_i^{\pm} - D_{ij}^{\pm}) \leq Q_j^{\pm} \tag{11}$$

$$L_i \leq W_i^{\pm} \tag{12}$$

$$0 \leq W_i^{\pm} - D_{ij}^{\pm} \leq U_i \tag{13}$$

$$0 \leq D_{ij}^{\pm} \tag{14}$$

where $OF_{ON}$ is the optimal value of the solution obtained from the policy of non-trading.

The constraints of this policy are:

The total benefit of the system under the trading policy must be greater than or equal to the maximum optimal benefit of the system under the non-trading policy (Equation (9)). The water consumption of the whole system should be less than the total amount of permits (Equation (10)). The total system access to water is limited to the total system water access in the trading program (Equation (11)). The water consumption of each user is less than or equal to his maximum water requirement such as non-trading policy.

The upper and Lower fuzzy bounds are:

$$Min\ OF_T^{+} = \sum_{i=1}^{n} (W^{+})_i - \sum_{j=1}^{m} P_j D_{ij}^{-}$$

S.t.

$$\begin{gathered}
\left( \sum_{i=1}^{n} (B^{+}W^{+})_i - \sum_{i=1}^{n} \sum_{j=1}^{m} D_{ij}^{-} P_j C_i^{-} \right) \geq OF_N^{+} \\
\sum_{i=1}^{n} W_i^{+} \leq \sum_{i=1}^{n} G_i \\
\sum_{i=1}^{n} (W_i^{+} - D_{ij}^{-}) \leq Q_j^{+} \\
L_i \leq W_i^{+} \\
0 \leq W_i^{+} - D_{ij}^{-} \leq U_i \\
0 \leq D_{ij}^{-}
\end{gathered} \tag{15}$$

$$Min\ OF_T^{-} = \sum_{i=1}^{n} (W^{-})_i - \sum_{j=1}^{m} P_j D_{ij}^{+}$$

S.t.

$$\begin{aligned}
&\left(\sum_{i=1}^{n}(B^{-}W^{-})_i - \sum_{i=1}^{n}\sum_{j=1}^{m}D_{ij}^{+}P_jC_i^{+}\right) \geq OF_N^{-}\\
&\sum_{i=1}^{n}W_i^{-} \leq \sum_{i=1}^{n}G_i\\
&\sum_{i=1}^{n}(W_i^{-} - D_{ij}^{-}) \leq Q_j^{-}\\
&L_i \leq W_i^{-}\\
&0 \leq W_i^{-} - D_{ij}^{+} \leq U_i\\
&0 \leq D_{ij}^{+}
\end{aligned} \tag{16}$$

## CASE STUDY

Jilin Province is located at 40°52′ to 46°18′N, 121°38′ to 131°19′ in Northeast China with a temperate continental monsoon climate. The average rainfall of Jilin Province is 610 mm per year, and the rainfall pattern gradually decreases from east to west (Zheng *et al.* 2020). The studied area has a vast agricultural plain area with fertile soil. Therefore, it is one of the most important production areas in China and plays an important role in ensuring the security of national grains. An area of the eastern part of the province whose major products are summarized in Table 1 was evaluated. These products consume nearly 78% of the total water used in the agricultural sector in this area, and their total yield is nearly 96% of the total production. Planting area, irrigation water, economic value of water consumption, and other input information of the model are shown in this table. The total available water in a water year is estimated to be 22.4 million cubic meters. If it is divided according to the area under cultivation, it is summarized as water availability in column 6 of the table. The required water (column 7) is equal to the water required by the plant based on the estimation of potential transpiration method (Allen *et al.* 1998). Probable rainfall (column 9) is estimated based on a 25-year return period. Water permit (column 8) is determined by estimating water losses, effective rainfall and water demand. Cultivated area, irrigation, economic value and product have also been recorded using field information by completing a questionnaire based on real conditions.

### Water allocation results based on trading policy

Table 2 shows the volume of water allocated to each plant based on the no-trade policy under normal conditions and fuzzy limits. In addition, the amount of water shortage (*D*) and the profit from saving water consumption have been estimated. As

**Table 1** | Summary of water budget and cultivation pattern of the study area

| 1 Crop | 2 Area ha | 3 Yield kg/ha | 4 Irrigation $m^3.ha^{-1}$ | 5 Economic value $Yuan.m^{-3}$ | 6 Water availability $10^3\,m^3$ | 7 Water demand $m^3.ha^{-1}$ | 8 Water permit $m^3.ha^{-1}$ | 9 Rainfall probability mm |
|---|---|---|---|---|---|---|---|---|
| Wheat | 314 | 4,810 | 5,140 | 0.89 | 3,132 | 3,180 | 4,990 | 137 |
| Barley | 415 | 3,910 | 4,790 | 0.81 | 4,139 | 3,075 | 4,780 | 137 |
| Corn | 225 | 8,110 | 9,640 | 1.38 | 6,233 | 4,280 | 7,800 | 76 |
| Carrot | 125 | 24,620 | 7,450 | 1.07 | 1,247 | 4,360 | 7,538 | 31 |
| Sorghum | 376 | 56,400 | 6,180 | 1.64 | 3,750 | 2,990 | 4,402 | 98 |
| Alfalfa | 268 | 12,420 | 11,260 | 1.25 | 2,673 | 7,860 | 10,936 | 64 |
| Garlic | 37 | 6,940 | 8,190 | 2.11 | 369 | 4,420 | 7,726 | 23 |
| Millet | 16 | 1,780 | 7,120 | 0.92 | 160 | 4,045 | 7,141 | 14 |
| Sesame | 70 | 1,060 | 5,780 | 2.32 | 698 | 3,890 | 6,732 | 27 |
| Total | 2,246 | | | | 22,400 | | | |

**Table 2** | Components of water allocation based on the non-trading policy

| | $W^-$ | $W^+$ | $W^\pm$ | $D^-$ | $D^+$ | $D^\pm$ | Net benefit | | |
|---|---|---|---|---|---|---|---|---|---|
| Crop | $m^3.ha^{-1}$ | | | $m^3.ha^{-1}$ | | | $Yuan.ha^{-1}$ | | |
| Wheat | 3,714 | 4,826 | 4,211 | 1,426 | 314 | 929 | 1,269 | 279 | 827 |
| Barley | 3,528 | 4,469 | 3,986 | 1,262 | 321 | 804 | 1,022 | 260 | 651 |
| Corn | 6,482 | 7,800 | 7,685 | 3,158 | 1,840 | 1,955 | 4,358 | 2,539 | 2,698 |
| Carrot | 5,864 | 6,981 | 6,625 | 1,586 | 469 | 825 | 1,697 | 502 | 883 |
| Sorghum | 3,150 | 4,398 | 4,158 | 3,030 | 1,782 | 2,022 | 4,969 | 2,922 | 3,316 |
| Alfalfa | 8,670 | 10,820 | 9,854 | 2,590 | 440 | 1,406 | 3,238 | 550 | 1,758 |
| Garlic | 5,798 | 7,451 | 7,018 | 2,392 | 739 | 1,172 | 5,047 | 1,559 | 2,473 |
| Millet | 6,285 | 6,940 | 6,524 | 835 | 180 | 596 | 768 | 166 | 548 |
| Sesame | 4,218 | 5,375 | 5,049 | 1,562 | 405 | 731 | 3,624 | 940 | 1,696 |

shown in the table, based on the no-trade theory, the amount of water saving for sorghum and corn was 2,022 and 1,955 cubic meters per hectare, respectively. It is reminded that the amount of water allocated to each product in the non-trading policy is optimal for the same product and is not exchanged between other plants. The profit from the non-trading policy for wheat ranges from 279 to 1,269 Yuan/ha, which shows that the fuzzy inference system can have a significant effect on the answer to the problem. The highest profit for saving water consumption has been calculated for sorghum and the lowest profit for millet. Sorghum is a plant that is resistant to drought stress, and stress control during the growth period can lead to a 35% saving in water consumption and an increase in net profit.

Table 3 shows the volume of water allocated to each plant based on the no-trade policy under normal conditions and fuzzy limits. In addition, the amount of water shortage (*D*) and the profit from saving water consumption have been estimated. As shown in the table, based on the no-trade theory, the amount of water saving for sorghum and corn was 2,022 and 1,955 cubic meters per hectare, respectively. It is reminded that the amount of water allocated to each product in the non-trading policy is optimal for the same product and is not exchanged between other plants. The profit from the non-trading policy for wheat ranges from 279 to 1,269 Yuan/ha, which shows that the fuzzy inference system can have a significant effect on the answer to the problem. The highest profit for saving water consumption has been calculated for sorghum and the lowest profit for millet. Sorghum is a plant that is resistant to drought stress, and stress control during the growth period can lead to a 35% saving in water consumption and an increase in net profit.

In order to provide a general comparison of the difference in net profit and water saved in trading and non-trading societies, Figure 2 is drawn. As shown in the figure, the highest water saving was obtained for sorghum. Irrigation planning for this

**Table 3** | Components of water allocation based on the trading policy

| | | | | | | | Net benefit | | |
|---|---|---|---|---|---|---|---|---|---|
| Crop | $W^-$ $m^3.ha^{-1}$ | $W^+$ $m^3.ha^{-1}$ | $W^\pm$ $m^3.ha^{-1}$ | $D^-$ $m^3.ha^{-1}$ | $D^+$ $m^3.ha^{-1}$ | $D^\pm$ $m^3.ha^{-1}$ | $Yuan.ha^{-1}$ | | |
| Wheat | 3,268 | 4,618 | 3,958 | 1,872 | 522 | 1,182 | 1,666 | 465 | 1,052 |
| Barley | 3,323 | 4,218 | 3,723 | 1,467 | 572 | 1,067 | 1,188 | 463 | 864 |
| Corn | 6,735 | 8,360 | 8,135 | 2,905 | 1,280 | 1,505 | 4,009 | 1,766 | 2,077 |
| Carrot | 5,628 | 6,817 | 6,541 | 1,822 | 633 | 909 | 1,950 | 677 | 973 |
| Sorghum | 3,214 | 4,447 | 4,213 | 2,966 | 1,733 | 1,967 | 4,864 | 2,842 | 3,226 |
| Alfalfa | 8,908 | 11,228 | 10,840 | 2,352 | 32 | 420 | 2,940 | 40 | 525 |
| Garlic | 5,976 | 7,893 | 7,416 | 2,214 | 297 | 774 | 4,672 | 627 | 1,633 |
| Millet | 5,893 | 6,374 | 6,085 | 1,227 | 746 | 1,035 | 1,129 | 686 | 952 |
| Sesame | 4,618 | 5,768 | 5,642 | 1,162 | 12 | 138 | 2,696 | 28 | 320 |

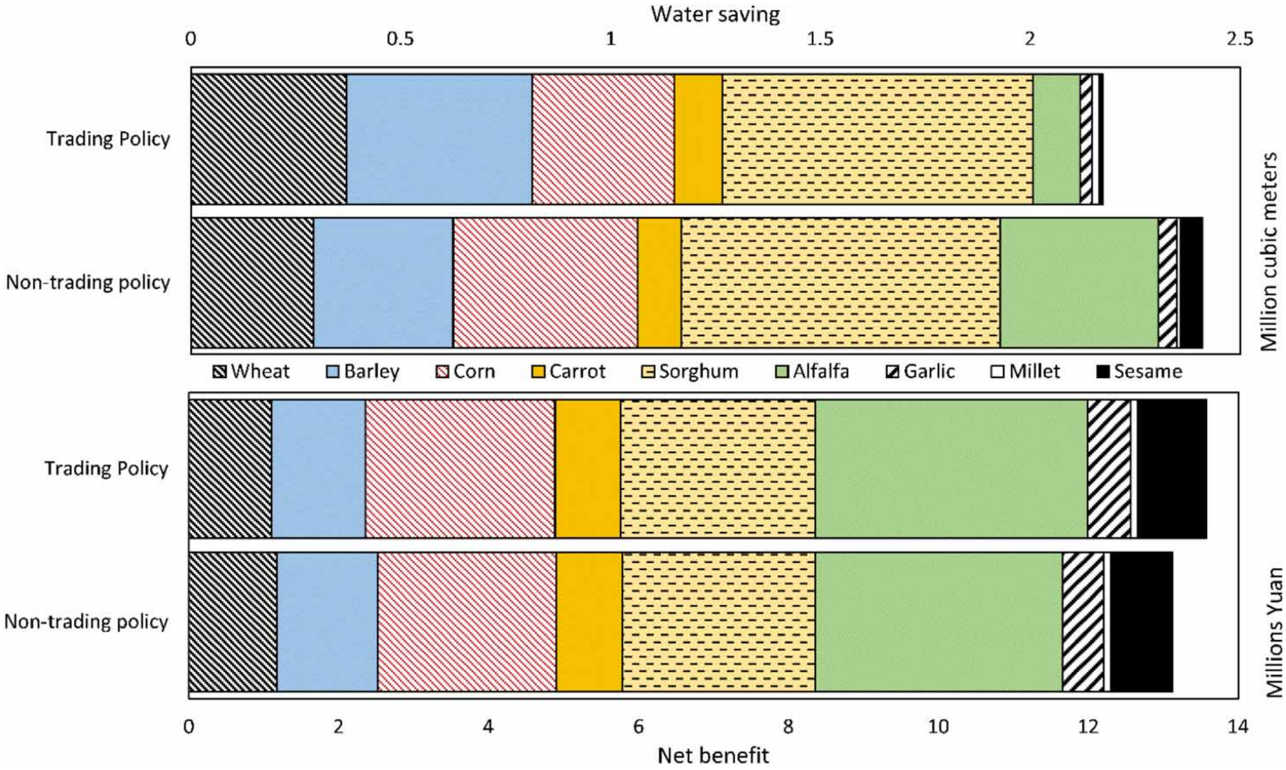

**Figure 2** | Water saving and net benefit estimated by trading and non-trading policies.

plant in real conditions has been with high losses. Therefore, the optimization has led to an increase in the profit from saving water (Fang & Tang 2023). In addition, the highest profit has been calculated for alfalfa. Alfalfa is a plant that grows throughout the year and has a high yield and net profit. Increasing the efficiency of water use, especially in terms of trading, increases the profit from the cultivation pattern for the beneficiaries. Results showed that, in general, the trading policy will increase the profit from changing the water allocation pattern, and the non-trading policy will reduce water consumption savings (Zhang *et al.* 2019).

## CONCLUSION

This study is based on the optimization of water consumption in agriculture based on two trading and non-trading policies. In the trading policy, the amount of water allocated to the cultivation pattern will be divided between the plants based on the optimization model. This policy increases the water allocated to plants with higher economic value. Therefore, the net profit of farmers in the trading method is more than no trading. In the non-trading method, water consumption is saved by maximizing the economic benefits of farmers without changing the cultivation pattern. The results showed that the trading policy can reduce between 4 and 47% of water consumption compared to real conditions. Fuzzy analysis in trading and non-trading policies determined the critical limits of water allocation and the resulting profit. Planning based on fuzzy logic reduces the risk of failure of the decision-making system.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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