Irrigation Decision-making Methods

Based on Multi-source Irrigation Information Fusion

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Abstract: According to the problem that uncertainty information is difficult to be merged during the decision process of multi-source irrigation information, a fusion method based on fuzzy rough sets and D-S evidence theory was proposed. Using the fuzzy rough set theory, the basic probability assignment function (BPAF) was established, the interdependence between irrigation factors and irrigation decision was calculated, and the frame of discernment was built. Using the improved Dempster-Shafer (D-S) evidence theory, the multi-source irrigation information was fused at the decision-making level, the expression and synthesis problems of uncertain information were solved. The information of cotton, such as CWSI, soil moisture, and stomatal conductance, were fused in irrigation decision. The results showed that the uncertainty of the irrigation decision decreases from 39.0% before fusion to 6.57%. The method could effectively improve the accuracy and reduce the uncertainty of irrigation decision making.

Introduction

In the 21st century, the scarce water resources are becoming a kind of precious resources. Water resources problem is not just a matter of resources. It maybe a major strategic issue which is more related to the national economy, sustainable development and the long-term national stability. With the increase of the population, and the high development of industry and agriculture, water resources crisis is intensified, the problem of shortage of water resources has evolved into a worldwide problem, and the efficient utilization and protection of water resources has become a focus of global attention[1]. Therefore, it has an important strategic significance of the sustainable development of agriculture, to strengthen management and reasonable allocation of water resources, to improve the utilization efficiency of water resources, to promote the sustainable and healthy development of economy and society, and to realize accurate irrigation.

Due to the fact that most of the water needed by crops is stored in the soil, and then it is supplied to the crops, the determination of field irrigation planning and institution is adopted by the soil moisture. Although the soil moisture was indirect to crop growth, it could well reflect the supply of crop water. At the same time, the measurement of soil moisture was relatively easy, and it was currently the main information source to reflect crop water status. In addition, because the real object of irrigation is the crop instead of soil, crop water status information is collected directly

from the crop. It is a direct characterization of crop water physiological process. Therefore, the directly obtained information of physiology and ecology which is closely related to crop water use, could quickly, directly and accurately reflect crop water status, and it was also a valuable source of information[2]. To sum up, because the soil moisture and crop physiological indexes in essence reflect the degree of crop water shortage, if using only one or two factors (such as soil moisture) to do the irrigation, it may lead to the waste of water resource, and even affect the normal growth of crops. Therefore, in order to realize accurate irrigation, a variety of irrigation indicators should be considered to guide the irrigation decision making.

The emergence of multi-source information fusion technology made it possible to the multi-index decision. The provided information of each decision index had the different ways, credibility, different uncertainty and different emphasis[3,4]. In order to improve the precision of irrigation management and decision making, how to integrate and process the decision indexes timely and effectively, and how to solve a series of uncertainty problems appeared in the process of fusion[5,6], are currently the problems of multi-source information fusion in the field of farmland irrigation.

The multi-source information fusion technology was introduced into the irrigation area, so as to eliminate the possible redundancy and the contradiction between multi-source irrigation information, to reduce the uncertainty of irrigation decision-making information and the fuzzy degree of decision reasoning, to improve the reliability of irrigation decision, and to solve the problems of information fusion in the irrigation area. The research of irrigation decision information fusion methods had a certain practical significance, to solve some difficult points and key problems in the process of irrigation decision-making, to improve the utilization efficiency of irrigation information and the ability to correct decision in the changeable environment, to realize the irrigation information value-added and the irrigation management mode of new generation.

Material and Methods

Site Description. The experiment was conducted during the period of April to October, 2014, at the comprehensive test station in Xinxiang city of CAAS, located in Qiliying town of Xinxiang county (35◦18’N, 113◦54’W, and 73.2 m elevation). The station is in a sub-humid, temperate and monsoon climate zone. The annual mean temperature is 14.1˚C, average annual sunshine duration is 2398.8 h, annual frost-free days are 210 d; mean annual precipitationis 582 mm, and the mean potential evaporation (measured with the pan of 20 cm diameter) 2000 mm. The soil is loam. Soil samples were taken every 20 cm from 0 to 1.0 m in 2014, and then the bulk density and field capacity were determined. The mean bulk density is 1.51 mg m^{-3}, and mean field capacity is 20.5% (mass basis) in the 0 m–1.0 m soil profile. Water table was always deeper than 5 m during the study.

Experimental Design. Spring cotton variety was ‘Zhongmian 60’, It was sowned on April 24, 2014, and the whole growth period was over on October 27, 2014. Wide-narrow row planting was used, and the width of wide row and narrow row was 1.0 m and 0.5 m respectively, the planting density was 4.5×10^4 plants/hm^2, the area of each experimental plot was 13.5 m×25 m. A SDI system was installed prior to sowing in 2014. The SDI system was designed and managed to ensure uniform application. The drip irrigation belt was spreaded between the rows of cotton, the flow rate of the drop head was 2.0 L•h^{-1}, the sufficient water supply was taken in the whole stage of the spring cotton, the irrigation quota was 30 mm (water meter measurement). Cotton topping was in mid-July, The field was monitored for insects and diseases, and pesticides were applied as needed. Weed control was achieved using herbicides.

Measurements. Meteorological data on air temperature, relative humidity, solar radiation, wind speed and precipitation, were provided by an automatic meteorological station located in the test site, about 1.0 km distance from the cotton field. Soil samples were collected using a soil corer at 20cm increments down to 100cm in all experimental plots. The soil moisture content (gravimetric water content, %) was determined using the oven-drying method every 7 days. A porometer (AP4-UM-3, Delta-T Devices, UK) was used to measure leaf stomatal conductance (G_s) at 7 *d* interval during the growing season. The selected plants were the same, and the leaves were fully expanded. On both sides of each selected leaf were measured. In order to assess canopy temperature, infrared images were obtained manually with an infrared thermal image instrument (Infrec G100EX, Japan), with a resolution of 240×320 pixels that operates in the wave band range of 8–14 *mm*. The instrument had a tempreture resolution of 0.04°C and the accuracy of absolute temperature measurement is less than ±2°C. Throughout the entire experiment, the emissivity for canopy was set at 0.96, which is within a range quoted for plant leaf by J. Padhi[7].

CWSI calculations. CWSI has been used for assessing the water status of crops , such as grapevine [8,9], wheat[10], maize[11] and cotton. The CWSI [12] commonly varied between 0 and 1. Values close to 0 indicated a fully transpiring leaf (i.e. no stress), whereas values close to 1 indicated a non-transpiring leaf/crop (i.e. maximum stress). According to Jones' empirical formula, the canopy water stress index[13] was calculated using Eq. 1.

$$CWSI = \frac{T_c - T_w}{T_{dry} - T_w} \quad . \tag{1}$$

where T_c was the temperature (°C) of the crop canopy (average of the leaves within a polygon drawn on the infrared thermal image) at the time of the thermal image, the dry baseline temperature(T_{dry}) was estimated by adding 5°C to the maximum dry bulb temperature, and T_w was the average temperature of a wet reference that acted as a substitute for the well-watered base line temperature. Because the wet reference temperature (T_w) required in Eq. 1 requires the movement, maintenance and establishment of a physical wet reference body, it is difficult to use for routine monitoring. An alternative T_w value can be estimated using Eq. 2[14].

$$T_w \approx T_a - \frac{e_s(T_a) - e_a}{\Delta + g} \quad . \tag{2}$$

where T_a is air temperature (°C), e_s is saturated vapor pressure (P_a) at T_a, e_a is actual vapor pressure (P_a), Δ is slope (P_a•°C^{-1}) of the saturated vapor pressure vs. temperature curve evaluated at (T_a), and g is the psychometric constant (P_a•°C^{-1}).

Establish BPAF Based on Fuzzy Rough Sets

In the process of information fusion of target recognition based on evidence theory, the acquisition of basic probability assignment function (BPAF) was closely related to the object of application, BPAF was the key to information fusion. According to the characteristics of the irrigation information management and decision making, the fuzzy rough set theory was introduced, and the fuzzy set membership function was used to replace the BPAF[15-17]. Membership function was determined mainly by the characteristics of the measured indexes. In this paper, the triangular membership functions are defined using Eq. 3 and Eq. 4.

$$m_1 = \begin{cases} 1, & x \le d_1 \\ \left(\dfrac{d_2 - x}{d_2 - d_1}\right)^2, & d_1 < x < d_2 \\ 0, & x \ge d_2 \end{cases} . \tag{3}$$

$$m_2 = \begin{cases} 0, & x \le d_1 \\ \left(\dfrac{x - d_1}{d_2 - d_1}\right)^2, & d_1 < x < d_2 \\ 1, & x \ge d_2 \end{cases} . \tag{4}$$

Where m_1 and m_2 were the membership functions under the condition of drought and appropriate water respectively.

BPAF was defined using Eq. 5.

$$\begin{cases} m(A_1) = m_1 \\ m(A_2) = m_2 \\ m(\Theta) = 1 - m(A_1) - m(A_2) \end{cases} . \tag{5}$$

Where A_1 and A_2 were under the condition of drought and appropriate moisture, Θ was the frame of discernment, $\Theta = \{A_1, A_2\}$.

Fusion Algorithm

D-S Evidence Theory. D-S evidence theory[18,19] is a mathematical tool developed in 1970s. It is an extension of the bayesian theory. D-S evidence theory doesn't need a priori information. The method of 'range' is used to describe the uncertain information. It solves the uncertainty of the representation information. In the aspect of the difference between 'I don't know' and 'not sure', and accurate reflex of the aggregate evidence, it shows a lot of flexibility. D-S evidence theory has been widely applied in the fields of multi-source information fusion, target recognition and decision analysis. Basic theory of evidence was established in the published book of Mathematical Theory of Evidence by G. Shafer in 1976, on the basis of the 'upper and lower probability' and its synthesis rules which were proposed by A. P. Dempster in 1960s[20,21]. The theory is described as follows.

First, the frame of discernment Θ is defined, and it is made up by some incompatible and

exhaustive elements. m: $2^{\Theta} \rightarrow [0,1]$ is a mass function, if m meets the following conditions, ① $m(f)=0$, ② $\sum_{A \subseteq \Theta} m(A)=1$. And if $A < X$, $m(A) > 0$, then A is called the focal elements. If m_1, m_2, ...,and m_n are the mass functions on the identifying framework Θ, then, D-S combination rule can be obtained using Eq. 6.

$$m(A)=\frac{1}{1-K} \bullet \sum_{\substack{A_1, A_2, \mathbf{L}, A_n \subset \Theta \\ A_1 \cap A_2 \mathbf{L} A_n = A}} m_1(A_1) m_2(A_2) \mathbf{L}\ m_n(A_n) \quad . \tag{6}$$

$$K=\sum_{\substack{A_1, A_2, \mathbf{L}, A_n \subset \Theta \\ A_1 \cap A_2 \mathbf{L} A_n = \varnothing}} m_1(A_1) m_2(A_2) \mathbf{L}\ m_n(A_n) \quad . \tag{7}$$

where A is the intersection of focal elements A_1, A_2,...,A_n, Φ denotes a null set, K[22] is the conflict coefficient. The value of K(Eq.7) reflects the degree of conflict between evidences.

Fusion Algorithm. In order to improve the synthesis effect of conflicting irrigation factor, the choice of reasonable weight coefficient is very important. Through consulting relative literatures [23-28], and combining with the actual situation of irrigation factor information, the distance function was introduced, using the average irrigation factor to replace irrigation conflict factor, the combination problem of conflict irrigation factors was solved.

First, $\bar{m}_j$ which was the integrating irrigation factors for irrigation decision making, was calculated using Eq. 8, n was the number of integrating irrigation factors.

$$\bar{m}_j=\frac{\sum_{i=1}^{n} m_{ij}}{n} \quad . \tag{8}$$

Then, the distance d_i from each integrating irrigation factor to the average of the irrigation decision was calculated using Eq. 9.

$$d_i=e^{-|m_{i1}-\bar{m}_1|}+e^{-|m_{i2}-\bar{m}_2|}+\mathbf{L}+e^{-|m_{ij}-\bar{m}_j|}, i=1,2,\mathbf{K},n \quad . \tag{9}$$

Where m_{ij} denoted the supporting degree of the i integrating irrigation factor to the j irrigation decision.

Finally, the weight coefficient of each integrating irrigation factor irrigation and the new average evidence were calculated using Eq. 10 and Eq. 11.

$$w_i=\frac{d_i}{\sum_{i=1}^{n} d_i} \quad . \tag{10}$$

$$\overline{m}'=w_i m_i \quad . \tag{11}$$

Where w_i was the weight coefficient of the ith irrigation factor, the sum of w_i was

1, $\sum_{i=1}^{n} w_i = 1$。

Before fusion, the conflict coefficient K was calculated using Eq. 7, if K is less than the preset value, the information of multi-source irrigation is fused using Eq. 6. If K is greater than the preset value, the weight coefficient of each irrigation factor is determined firstly, and then, the information of integrating irrigation factors which causes the conflict needs to be modified in the frame of discernment. The steps were as follows.

(i) The frame of discernment was built, and the basic probability function of each integrating irrigation factor was assigned, the matrix was shown using Eq. 12 .

$$M = \begin{bmatrix} M_1 \\ M_2 \\ \mathbf{L} \\ M_n \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & \mathbf{L} & m_{1m} \\ m_{21} & m_{22} & \mathbf{L} & m_{2m} \\ \mathbf{L} & \mathbf{L} & \mathbf{L} & \mathbf{L} \\ m_{n1} & m_{n2} & \mathbf{L} & m_{nm} \end{bmatrix}. \tag{12}$$

Where m_{ij} denotes the supporting degree of the *ith* integrating irrigation factor to the *jth* irrigation decision making , it met the condition of $\sum_{j=1}^{m} m_{ij} = 1$,(i=1,2,3,...n)。

(ii) The row *i* of the matrix *M* was transposed, then M_i^T was multiplied with another row *j* of the matrix M_j, the matrix was shown using Eq. 13 .

$$M_i^T \times M_j = \left[m_{i1} m_{i2} m_{i3} \ \mathbf{L} \ m_{im}\right]^T \cdot \left[m_{j1} m_{j2} m_{j3} \ \mathbf{L} \ m_{jm}\right]. \tag{13}$$

(iii) A new matrix *A* (m×m)(Eq.14) was generated. The diagonal elements were removed, the sum of all the other elements of the matrix constitute the uncertainty factors K'(Eq. 15) of the integrating irrigation factors.

$$A = \begin{bmatrix} m_{i1} \times m_{j1} & m_{i1} \times m_{j2} & \mathbf{L} & m_{i1} \times m_{jm} \\ m_{i2} \times m_{j1} & m_{i2} \times m_{j2} & \mathbf{L} & m_{i2} \times m_{jm} \\ \mathbf{L} & \mathbf{L} & \mathbf{L} & \mathbf{L} \\ m_{im} \times m_{j1} & m_{im} \times m_{j2} & \mathbf{L} & m_{im} \times m_{jm} \end{bmatrix}. \tag{14}$$

$$K' = \sum_{p \neq q} m_{ip} \times m_{kq} \ (p, q = 1, 2, 3 \ \mathbf{L} \ m). \tag{15}$$

(iv) Finally, the multiple irrigation factors were fused using Eq. 16.

$$m_j = M_{jj} / (1 - K'). \tag{16}$$

Results

Based on the measurement of cotton irrigation index (CWSI, soil moisture (gravimetric water content), and stomatal conductance) and its critical value [29-34], membership functions were constructed.

Using CWSI as the fusion factor, the membership functions were built.

$$m_1 = \begin{cases} 1, & x \le 04 \\ \left(\dfrac{1-x}{0.6}\right)^2, & 0.4 < x < 1 \\ 0, & x \ge 1 \end{cases}$$

$$m_2 = \begin{cases} 0, & x \le 04 \\ \left(\dfrac{x-0.4}{0.6}\right)^2, & 0.4 < x < 1 \\ 1, & x \ge 1 \end{cases}$$

Using soil moisture as the fusion factor, the membership functions were built.

$$m_1 = \begin{cases} 1, & x \le 11.275 \\ \left(\dfrac{15.375-x}{4.1}\right)^2, & 11.275 < x < 15.375 \\ 0, & x \ge 15.375 \end{cases}$$

$$m_2 = \begin{cases} 0, & x \le 11.275 \\ \left(\dfrac{x-11.275}{4.1}\right)^2, & 11.275 < x < 15.375 \\ 1, & x \ge 15.375 \end{cases}$$

Using stomatal conductance as the fusion factor, the membership functions were built.

$$m_1 = \begin{cases} 1, & x \le 1.2 \\ \left(\dfrac{2.4-x}{1.2}\right)^2, & 1.2 < x < 2.4 \\ 0, & x \ge 2.4 \end{cases}$$

$$m_2 = \begin{cases} 0, & x \le 1.2 \\ \left(\dfrac{x-1.2}{1.2}\right)^2, & 1.2 < x < 2.4 \\ 1, & x \ge 2.4 \end{cases}$$

In order to verify the effectiveness of the algorithm, take the measured data on July 26, 2014 for example, the values of CWSI, soil moisture, and stomatal conductance were 0.48, 12.119%, 2.07 $cm \cdot s^{-1}$ respectively, according to the established membership functions, the basic probability assignment (BPA) calculated were shown in Table 1.

Table 1 BPA of each irrigation factor

Irrigation factors	Irrigation	Non-irrigation	Uncertainty
CWSI	0.76	0.02	0.22
Soil Moisture[%]	0.63	0.04	0.33
Stomatal Conductance[$cm \cdot s^{-1}$]	0.08	0.53	0.39

Table 1 showed that the irrigation indicator of stomatal conductance was in conflict with the other two indicators. According to the supporting degree, the frame of discernment Θ was built,

$\Theta = \{\text{Irrigation, Non-Irrigation, Uncertainty}\}$. First, the conflict coefficient K was calculated using Eq. 7, because K=0.933>0.65, the fusion was done using Eq. 8 to Eq. 16 . The fusion results were showed in Table 2.

Table 2 Fusion results according to irrigation decision indicators of spring cotton

Fusion results of irrigation decision	Irrigation	Non-irrigation	Uncertainty
Fusion results	0.9513	0.0002	0.0657

From Table 1and Table 2, we could see that the probability of irrigation decision making increased from the minimum 8% before fusion to 95.13%, the uncertainty of the irrigation decision decreased from 39.0% before fusion to 6.57%. The results showed the above method could effectively improve the accuracy and reduce the uncertainty of the irrigation decision making.

Discussion

To a certain extent, using the above method, the accuracy of the irrigation decision-making was improved and the uncertainty was reduced, however, there were still some shortcomings in the process of application. The following points should be included in the future research:

(i) According to different kinds of data source, crops and irrigation methods, different types of membership functions should be set up, and a variety of discernment frame of irrigation decision be constructed.

(ii) In order to further improve the fusion accuracy, the fusion methods mentioned above should be perfected.

(iii) With the development of multi-source information fusion technology, different fusion methods could be applied.

Conclusions

Through systematic research, the following conclusions were worked out.

(i) Using the theory of fuzzy rough set, basic probability assignment functions were constructed, the supporting degree between each integrating irrigation factor and irrigation decision was calculated, thus, the uncertain effect of subjective factors was effectively avoided, and the irrigation decision results became more objective.

(ii) Using the modified D-S evidence theory, the distance functions were introduced to determine the weight coefficient of multi-source irrigation factor, the construction of the belief degree matrix completed a combination of multi-source irrigation factors, the problem of multi-source information fusion was effectively solved, and the precision of irrigation decision was improved.

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