Risk evaluation of solar greenhouse cucumbers low temperature disaster based on GIS spatial analysis in Tianjin, China

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ABSTRACT
To plan the cucumber cultivation area scientifically, improve the quality of cucumber and avoid meteorological disaster risks, this article evaluates low temperature disaster risk of greenhouse cucumber in Tianjin, China. Solar greenhouses are the main carriers for facility agriculture in North China which usually do not carry heating and supplementary lighting equipments. Consequently, growth and development of crops are still indirectly influenced by the greenhouse outside weather in some extent. In recent years, low temperature disaster of cucumber during overwintering periods happens frequently which brings large influence on cultivation and production of cucumbers in Tianjin. This research takes three types of solar greenhouses with different heat-retaining capacities as the facility carriers to evaluate the low temperature disaster risk of cucumbers grown in different greenhouses. First, study the corresponding relationship between microclimate elements in greenhouse and meteorological elements out of greenhouse based on assurance rate method and conduct the indexes caused cucumber low temperature disaster in different greenhouses at different development stages. Then, construct the risk evaluation model for low temperature disaster based on natural disaster risk evaluation theory. Finally, the low temperature disaster risk zone-division is realized based on GIS spatial analysis function to evaluate cucumber low temperature disaster risk comprehensively.

Abbreviations: SG: solar-greenhouse; Cucu: cucumber; LTD: low temperature disaster; RE: risk evaluation; GIS: geographic information system; TJ: Tianjin

1. Introduction
In recent years, greenhouse culture has become the important part of facility agriculture. Be different from other agricultural production methods, greenhouse culture has itself
characteristics which are conducted in special agricultural facilities – greenhouse. The main environmental restrictive factors for the crop growth and development in greenhouse include illumination, temperature, humidity and ventilation conditions, in which temperature is one of the most important environmental factors (Yağcıoğlu 2005). Suitable temperature and humidity conditions not only contribute to the growth and development of crops, but also contribute to reduce disease of greenhouse crops and use of insecticide, which is helpful for obtaining of high quality agricultural products.

In the past 20 years, the intensive facility agriculture has rapidly developed in some developed countries, such as Holland, America, Spain and Japan which have formed a considerably powerful pillar industry. The importance of greenhouse in agricultural production is increasingly prominent which can guarantee the optimal heat condition in each crop growth stage and supply ample agricultural products with high quality in non-crop growth season (Bennis et al. 2008; Sethi and Sharma 2008). The facility agriculture advanced countries with the representative of Holland have high agricultural facility standardization degrees, most of them are connected and intelligent greenhouses which have standard planting techniques and cultivation techniques, as well as advanced plant protection technique, facility environment comprehensive adjustment and control technique and agriculture mechanical technique. Also, they are on the way to automation, intelligent and networking orientation (Wang 2010). Therefore, the greenhouses of these countries are little influenced by meteorological disasters. Since 1980s, the facility agriculture with the representative of solar greenhouses and plastic greenhouses have been rapidly developed in China, especially, the energy-saving solar greenhouses which adapt to the economic technical level in rural areas in China have been rapidly developed in areas of the middle and lower reaches of the Yellow River including Huang-Huai Plain, Liaodong Peninsula as well as Peking and Tianjin region (Wang 2010). At present, the facility culture in China occupies more than 85% of the whole world, and the total area and total production rank the first in the world. (http://news.1nongjing.com/a/201507/102403.html).

Facility agriculture has been the leading industry which increases agricultural production and income of peasants in China. Although there has been great progress in the facility agriculture in recent 30 years in China, the overall level is lagged behind the developed countries. According to the researches, the crop production will increase by 20% when the greenhouse temperature increases by 10°C (Canakci et al. 2013). Therefore, heating of greenhouse is quite important under insufficient radiation conditions. As the basic carrier of facility agriculture, neither plastic greenhouse nor solar greenhouse is equipped with microclimate control equipment in China because of the construction cost, which makes the facility crops benefit or damage from the outside weather to certain extent, i.e. the outside disastrous weather condition will still generate adverse influence on the growth and cultivation of facility agriculture crops (Sun 2012), and the disaster risks led by these adverse conditions are relatively serious. Therefore, compared with the countries with advanced facility cultivation techniques, the solar greenhouse crops and plastic greenhouse crops are easier to be influenced by the disastrous weather in China, with relatively high meteorological disaster risks, and with relatively high risks of facility crop disease and insect attack derived from meteorological disaster (Chen et al. 2014). It is essential to develop research on
facility crop meteorological disaster risk evaluation based on the relationship between greenhouse outside or inside meteorological condition and facility crops, and master the occurrence regularity and characteristics of facility crop meteorological disaster, and analyse the possible disaster loss for facility crop to provide scientific basis for the preventing disaster and reducing damage of facility agriculture.

Some researchers have conducted a large number of researches aiming at the risk evaluation on the meteorological disaster of facility agriculture. Considering the stable and developed facility agriculture system of the facility agriculture has been formed in developed countries, which can conduct automatic environment control in the facilities according to the optimum ecological conditions for crop growth, which is not influenced by climatic conditions. Therefore, the risk evaluation usually focuses on the economic risk, social risk and environment risk (Carter 1995; Piers 1998). And it pays more attention to the facility crop pest and disease damage caused by adverse facility inside microclimate, for example the downy mildew of greenhouse cucumber (Shetty et al. 2002; Colucci 2008; Arauz et al. 2010) and the *Bemisia tabaci* of greenhouse tomato (Stansly et al. 2004). Some researchers in China have worked a lot on facility agriculture meteorological disaster, for example Wei and Zhao studied the indexes and grade for low temperature and sunlight shortage disaster of greenhouse vegetables in Hebei Province, China, and obtained the suitable meteorological factor for vegetables in solar greenhouse by consideration of the meteorological conditions needed for growth of vegetables as well as the crop yield loss after low temperature & sunlight shortage disaster (Wei and Zhao 2005); Cai et al. conducted risk grade division to three main meteorological disasters (sunlight shortage disaster, low temperature disaster and high temperature disaster) in the facility agriculture area in Jiangsu Province, China (Cai et al. 2011); Huang et al. studied the quantitative criteria for solar greenhouse wind disaster grading and conducted evaluation on the time and space change of wind disaster of solar greenhouse (Huang et al. 2012); Yang et al. constructed solar greenhouse meteorological disaster risk evaluation model based on accelerating genetic algorithm with real number encoding (Yang et al. 2012). We can find out from the above researches (especially those from Chinese scholars) that they usually focused on meteorological disaster evaluation indexes of facility agriculture, the influence of multiple disaster indexes to facility agriculture and the critical values for disaster indexes of different disaster could be determined according to local practical situations. Some achievements have been applied in practice, but there are still some problems: 1) Different from field crops which are totally exposed to the outside natural environment, the greenhouse crops are grown in greenhouse which is directly influenced by the microclimate in the greenhouse, although they are influenced by the outside world environment in an indirect way. Most of the existing researches determine the meteorological disaster factors out of the greenhouse in the way of experience and spot investigation, which ignores the relationship between the factors in and out of the greenhouse and the direct influence of the meteorological factor in greenhouse on crops; 2) Most of existing researches take the whole growing period of greenhouse crops as the research object; in fact, there are different meteorological disaster influencing factors and influencing results for greenhouse crops in different developmental phases. Therefore, it is necessary to evaluate the meteorological disaster risks of greenhouse crops aiming at
different development phases; 3) Most researches ignore the influence of different greenhouse types on crop meteorological disaster evaluation, however, there are obvious differences in heat-retaining capacity between different greenhouse types, therefore, it is not proper to evaluate the greenhouse crop meteorological disaster by ignoring the influence of greenhouse types on crops.

Tianjin is a typical urban facility agriculture planting region in China, and cucumber is one of the most typical greenhouse crops in Tianjin. Cucumber is suitable to grow in warm but not high temperature conditions, and it is sensitive to low temperature. In recent years, the temperature conditions cannot meet the requirement for the normal growth of cucumber in solar greenhouse during overwintering period; consequently, there are frequent low temperature disasters which influence the growth and development of greenhouse cucumber. Besides, there show different characteristics in low temperature disaster in different development phases of cucumbers: 1) when encountering with low temperature during sprouting, the seed cannot sprout or with a slow speed; 2) when encountering with low temperature during seeding stage, the seed grow in a slow speed, with shortened inter nodes and dark green in colour; 3) when encountering with low temperature during blossom and yield fruiting period, the growth of the cucumber is obviously restrained, with shortened inter node and lamina, the fruit grow slowly (Pang and Qiao 2011). This research takes three typical solar greenhouses with different heat-retaining capacities in Tianjin as the facility carriers, takes greenhouse cucumber as the study object, and uses the meteorological observation data in and out of greenhouse, the cucumber growth observation data, the low temperature disaster experiment results and field investigation data accumulated by the research group as the data basis. First, study the correspondence relationship between microclimate factors in greenhouse and meteorological factors out of greenhouse based on the assurance rate method to construct the cucumber low temperature disaster indexes in and out of greenhouse for different development stages in different greenhouses. Then, based on the natural disaster risk evaluation theory, to construct the risk evaluation model for greenhouse cucumber low temperature disaster risk. Finally, the low temperature disaster risk zone-division of cucumber is realized of different greenhouses by utilizing Geographic Information System (GIS) spatial analysis function to evaluate the low temperature disaster risk of cucumber in a comprehensive way.

2. Study area and data

2.1. Study area

Tianjin is located in the northeast part of North China Plain in China (116°43–118°04E, 38°34–40°15N), and it is near to Yanshan Mountain to the north, and near to the Bohai Sea to the east, which is located in the transition region from mountain to strand plain; mountains and hills, plains and costal mud flat are distributed in Tianjin, with the coastline of more than 150 km. In recent years, because of the emerging of facility agriculture as well as the increase of area and production of facility vegetables and flowers, Tianjin becomes one of the main urban facility agriculture planting regions in China. The lowest temperature value of one year is present
in the middle ten days of January (the average value of the lowest temperature for many years is $-8.5\,^\circ C$), and the historical extreme lowest value of Tianjin is $-23.3\,^\circ C$ (the above data is provided by Tianjin Climate Center). Between the middle ten days of December and the first 10 d of February, the ground temperature is low and the duration of possible sunshine is little, in conditions of poor heat preservation or unreasonable crop rotation matching, it is easy for greenhouse crops to suffer from low temperature disaster. It can be obviously seen that the heat condition is the main restrictive condition for solar greenhouse crop in winter and spring, and it is useful to provide the effective meteorological disaster preventive measure during overwintering period in Tianjin (Figure 1) to evaluate low temperature disaster risk for greenhouse crops.

2.2. Study data

2.2.1. Meteorological data outside greenhouse
The hourly meteorological data outside greenhouse of 2005–2014 of 13 meteorological observation stations in Tianjin provided by Tianjin Climate Center, included temperature, sunshine duration, relative humidity, wind speed and wind direction.

2.2.2. Microclimate data inside greenhouse
The microclimate data inside greenhouse includes the inside greenhouse microclimate observation data (including air temperature, ground temperature, relative humidity and radiation) which is observed each 10 min of the three full over winter period (October–February of the next year) of 2011–2012, 2012–2013 and 2013–2014.
overwintering stubble cucumber of three typical solar greenhouse with different heat
retaining capacity (the three types of greenhouse are traditional second generation
greenhouse (located in Xiqing District, Tianjin), new type greenhouse (located in
Wuqing District, Tianjin) and traditional cob wall greenhouse (located in Baodi
District, Tianjin), and the introduction of various greenhouses, such as material or
structure will be shown in details in ‘2.3 Solar greenhouse introduction’. In order to
be in accordance with the time scale of greenhouse outside air temperature, this
research adopts the greenhouse inside air temperature of integral point time (e.g. 0,
1, 2, … … 23 o’clock) to make correspondence with the greenhouse outside air tem-
perature. Because of the lack of the microclimate data in some greenhouses and the
temperature in greenhouse is the key meteorological factor for impacting low tem-
perature disaster of greenhouse cucumber, the BP neural network based solar green-
house air temperature simulation model (Liu et al. 2015) is adopted in this research
to simulate the hourly air temperature in the greenhouse to fill up the deficiency of
greenhouse inside temperature. The model utilizes hourly outside temperature, out-
side daily sunshine duration, outside relative humidity and relative time to simulate
the hourly air temperature inside the greenhouse. In consideration of the data integ-
ritiy, the data of 2012–2013 is taken as the modelling data, and the data of 2011–2012
and 2013–2014 is taken as the verification data to test the hourly temperature simula-
tion result of the three types of solar greenhouses. Table 1 is the error analysis on
hourly air temperature simulation result of traditional Second generation greenhouse.
We can see from Table 1 that the maximum error between hourly air temperature
simulation value and the measured value is –1.92 °C, and the minimum error value
is 0.07 °C, and the average error is –0.35 °C, and the relative error value is 4%, and
the standard deviation is 3.03 °C. Generally, the simulation accuracy of hourly air
temperature can meet the requirement of the research. The hourly air temperature
simulated results of the other two types of greenhouses are similar with that of the
traditional second generation greenhouse, with the table ignored.

### 2.2.3. Cucumber yield data

The cucumber yield data of three typical greenhouses covered five overwintering peri-
ods, namely, 2010–2011, 2011–2012, 2012–2013, 2013–2014 and 2014–2015. The dis-
aster losses rates were computed with the cucumber yield reduction rate.

### 2.2.4. Other data (disaster experimental data and field investigation data)

In recent years, the research group has accumulated a large amount of greenhouse
cucumber low temperature disaster experimental data and field investigation data. In
consideration of the different morphological characteristics of cucumber in different
development phases, this research adopts cucumber low temperature disaster data for
different development phases to reflect the influence of low temperature disaster on
cucumber for different development phases. The research group developed low temperature disaster experiments on cucumber during seeding stage in October 2011 (2012)–November 2011 (2012) in the Sixth Port Village, Xiqing District and Shengrenzhuang Village, Baodi District in Tianjin, respectively. The experiments were designed at four low temperature levels of 6, 8, 10 and 15°C, with the low temperature processing time of 1–5 d and recovery time of 1–5 d, more details in the reference of Yu (2012). The low temperature disaster situation of cucumber during flowering phase and fruiting phase were based on the field investigation for the over-wintering periods of 2011–2012 and 2012–2013 of above two fields. After the end of the seeding phase, there was a special manager conducting low temperature disaster investigation to the assigned greenhouse each day, with the same person. The investigated position was at the southwest, northwest, middle, southeast and northeast corners of each greenhouse, presenting in X-shape. Three cucumbers are investigated for each position. The investigated items included the microclimate conditions of the plant (including air temperature, humidity, ground temperature and low temperature duration in greenhouse) and plant growth and development state (including plant height, leaf morphology, if there was damage and the damage degree, if the young fruit fell off, if the mature fruit deformed and the biomass).

2.3. Solar greenhouse introduction

By adopting three typical solar greenhouses with different heat-retaining capacities, this research conducts comparison and analysis on the low temperature disaster risk of cucumber for different development phases in three typical solar greenhouses. The material, structure and related parameters of various types of greenhouses are shown in Table 2. What shall be illustrated is that, compared with other two types of greenhouses, traditional cob wall greenhouse has obvious construction features, which shall be constructed in places with relatively wide land area, low-lying and low underground water level, i.e. a part of the greenhouse is buried underground, therefore, although there is no heating equipment, it has the optimal heat-retaining capacity.

3. Methodology and model

3.1. Growth and development phase of greenhouse cucumber

According to the growth and development data of greenhouse cucumber, the greenhouse cucumber is often planted before October 1st of each year in Tianjin; the seeding stage lasts for about 23 d; the stage of flowering without fruit lasts for about 10 d; the stage of flowering and fruiting lasts to May or June of the next year, but there is almost no low temperature disaster after the end of February; therefore, the growth and development phase of cucumber is determined as Table 3.

3.2. Indexes caused low temperature disaster for greenhouse cucumber

Tianjin has a large solar greenhouse constructing area, but it fails to realize to install the microclimate real-time monitoring system in each greenhouse. There are more
Table 2. Parameters of three types of solar greenhouses with different heat retaining abilities.

| Greenhouse type                          | Length (m) | Span (m) | Spine height (m) | Back wall height (m) | Back roof projection (m) | Side wall thickness (m) | Side wall material | Back wall thickness (m) | Back wall material | Back slope thickness (m) | Back slope material | Heat Curtain thickness (m) | Heat retaining performance |
|------------------------------------------|------------|----------|------------------|----------------------|--------------------------|------------------------|--------------------|-------------------------|---------------------|--------------------------|---------------------|-----------------------------|--------------------------|
| Xiqing traditional second generation greenhouse | 80         | 6.5      | 3.1              | 2.5                  | 0.67                     | 0.37                   | Brick              | 0.5                     | Brick               | 0.15                     | Cement              | 0.08                        | Poor                     |
| Wuqing new type greenhouse               | 65         | 9.97     | 5.22             | 3.72                 | 1.65                     | 0.5                    | ±                  | 0.5                     | Brick + polyphenyl board | 0.2                     | Cement              | 0.1                        | Moderate                 |
| Baodi traditional cob wall greenhouse     | 85         | 9        | 4.5              | 4.2                  | 0.88                     | 0.9                    | ±                  | 2.05                    | Soil                | 0.5                     | Soil                | 0.09                        | Excellent                |

Note: Thermal conductivity of wall material: brick – 0.75 W/m·K; soil – 0.23 W/m·K; polyphenyl board – 0.04 W/m·K; cement – 1.28 W/m·K.
than 200 evenly distributed meteorological automatic observation stations in Tianjin, and the real-time monitored meteorological elements observation network is basically formed. Therefore, obtaining greenhouse outside index caused low temperature disaster of cucumber is more practical and valuable for disaster risk evaluation at the regional scale. Considering that there are different morphological characteristics of cucumber in different development phases, different determination methods of disaster indexes are adopted aiming at different development phases: disaster index of the cucumber seeding phase is based on the past experiment results of this research group (Li 2013), the disaster index of the flowering phase and fruiting phase disaster index is based on the field investigation information of greenhouse cucumber planting area of Tianjin (Yu 2012), and greenhouse cucumber growth cultivation data is taken for reference (Ling and Wang 2009; Chen 2013; Li et al. 2013), to determine the cucumber greenhouse inside low temperature disaster index of different development phase. Based on the unified cucumber greenhouse inside low temperature disaster index, the assurance rate method is adopted to obtain the greenhouse outside indexes caused low temperature disaster for three types of greenhouses. The assurance rate method refers to the reliability degree of certain meteorological factor value is smaller or larger than some value, usually expressed with the accumulated frequency of some meteorological factor smaller or larger than some value in long period. As for the lower limiting value of greenhouse inside disaster index (i.e. greenhouse air temperature), rank the corresponding greenhouse outside disaster index (i.e. the greenhouse outside air temperature) from low to high to obtain the average value of 80% of the greenhouse outside air temperature at the back of the sequence, and take it as the lower limit of greenhouse inside disaster index; as for the upper limiting value of greenhouse inside disaster index (i.e. the greenhouse inside air temperature), rank the corresponding greenhouse outside disaster indexes (i.e. the greenhouse outside air temperature) from low to high, to obtain the average value of 80% of the greenhouse outside air temperature in front of the sequence, and take it as the upper limit of greenhouse outside disaster index which is corresponding to the upper limit of greenhouse inside disaster index.

3.3. Method for low temperature disaster intensity evaluation of cucumber in solar greenhouse

First, take the greenhouse outside air temperature of the overwintering period (October 1st of the year to February 28th (or 29th) of the next year is taken as the greenhouse cucumber wintering period in this research) of 2005–2006, 2006–2007, 2007–2008, 2008–2009, 2009–2010, 2010–2011, 2011–2012, 2012–2013, 2013–2014 of 13 meteorological observation stations in Tianjin as the basis to construct cucumber low temperature disaster indexes sequence. Then it conducts different theoretical probability density
function (such as Beta, Exponential, Gumbel, Gamma, Generalized Extreme Value, Inverse Gaussian, Logistic, Log-Logistic, Lognormal, Lognormal2, Normal, Pareto, Pareto2, Pearson Type V, Pearson Type VI, Weibull, etc.) fitting tests to disaster indexes sequence for different development phases and different disaster grades to select the optimal theoretical probability distribution function and calculate the probability value for different cucumber development phases and various disaster grade of 10 overwintering periods of 13 stations. Finally, calculate the average value of the 10 overwintering periods probability of each station to obtain the disaster intensity probability of cucumber low temperature disaster for different development phases and different disaster grades.

\[ I_{ik} = \frac{1}{n} \sum_{j=1}^{n} P_{ik,j} \]  

(1)

where \( I_{ik} \) represents the average intensity index of low temperature disaster for the \( i \) disaster grade (\( i = \) mild, moderate and severe respectively), \( k \) represents different development phase (\( k = \) seed, flowering and fruiting phase respectively), \( P_{ik,j} \) stands for the intensity probability for the \( i \) disaster grade and the \( k \) development phase, \( j \) represents the number of the \( k \) development phase, namely, \( j = 1, \ldots, 10 \).

Considering the disaster losses mainly happened during the fruiting phase, the comprehensive disaster intensity index was computed by assigning different weights for three-grade disaster intensity index. According to the different effect of different disaster grade, the weights were assigned 0.2, 0.3 and 0.5 for mild, moderate and severe disaster, respectively, namely,

\[ I_{ck} = \sum_{i,k=1}^{3} W_{ik} I_{ik} \]  

(2)

\( I_{ck} \) is the comprehensive disaster intensity index of low temperature disaster for the \( k \) development phase, \( W_{ik} \) represents the weights for the \( i \) disaster grade the \( k \) development phase, \( W_{ik} \) is equal to 0.2, 0.3, 0.5 for the mild, moderate and severe disaster, respectively.

### 3.4. Method for low temperature disaster losses evaluation of cucumber

Disaster losses evaluation means the yield losses caused by the low temperature disaster to the cucumbers. The yield losses evaluation index (\( G \)) represents the degree of disaster losses, which is computed by the disaster losses evaluation model of cucumber low temperature disaster, see Equation (3).

\[ G = \sum_{i=1}^{n} P_{i} \times Q_{i} \]  

(3)

where \( G \) represents disaster losses index, namely, yield losses index, \( P_{i} \) stands for the probability of different disaster grade of low temperature disaster, \( Q_{i} \) represents yield
reduction rate related to different disaster grade of low temperature disaster, \( i \) is different disaster grade of low temperature disaster, \( i = 1, 2, 3 \), namely, mild, moderate and severe, respectively, \( n \) is the number of disaster grades, \( n = 3 \). Refer to the computation of comprehensive disaster intensity index (Equation (2)), the weights are equal to 0.2, 0.3, 0.5 for the mild, moderate and severe disaster losses, respectively.

3.5. Method for disaster resistant capability evaluation of solar greenhouse

Heat retaining capacity of solar greenhouse is used to represent the disaster resistant capability of solar greenhouse. Heat retaining capacity is mainly related to the building parameters of solar greenhouses, such as wall material, wall thickness, span and ridge of the greenhouse and so on. The evaluation model of disaster resistant capability of greenhouses is constructed as Equation (4), according to the heat retaining capacity of the greenhouse is proportional to the thickness of the rear wall, inversely proportional to the ratio of the span to ridge (the ratio of span to ridge height), and inversely proportional to the thermal conductivity of the rear wall.

\[
R = \frac{F}{C \times \frac{S}{H}}
\]  

(4)

where, \( R \) is the index of disaster resistant capability of solar greenhouse; \( F \) is the thickness of greenhouse wall (m); \( C \) is the thermal conductivity of the wall material (W/m.K), \( S \) is span of greenhouse (m), \( H \) is ridge height (m). According to the greenhouse building parameters in Table 2, the index of disaster resistant capability \((R)\) is 0.0369, 0.0932 and 50 for the traditional second generation greenhouse, the new type greenhouse and the cob wall greenhouse, respectively.

3.6. Comprehensive risk evaluation of cucumber low temperature disaster

Comprehensive risk evaluation model of low temperature disaster of greenhouse cucumber was constructed based on the theory of natural disaster risk evaluation, see Equation (5),

\[
T = \frac{I \times G}{R}
\]  

(5)

where, \( T \) is the risk evaluation index of cucumber low temperature disaster; \( I \) is the average intensity index of low temperature disaster; \( G \) represents disaster losses evaluation index; \( R \) is the index of disaster resistant capability of solar greenhouses.

3.7. Ordinary Kriging interpolation method

In virtue of the spatial interpolation function of ArcGIS software (the Ordinary Kriging (OK) interpolation method is adopted in this research) to obtain the risk space distribution result for cucumber low temperature disaster for different development phases and different types of solar greenhouses.
OK uses a geostatistical model of reality and makes the following assumption:

\[
Z(s) = \mu + \varepsilon(s) \in D
\]

where \(\mu\) represents the constant mean structure of the concentration field, \(\varepsilon(s)\) is a smooth variation plus measurement error (both zero-mean) and \(D\) is the examining area (Denby et al. 2005; Hengl 2009).

The OK estimate is a linear weighted average of the available \(n\) observations defined in Equation (7) as:

\[
\hat{Z}(s_0) = \sum_{i=1}^{n} \lambda_i z(s_i), \sum_{i=1}^{n} \lambda_i = 1,
\]

Where \(\hat{Z}(s_0)\) is the OK estimate at location \(s_0\), \(z(s_i)\) is the measured value in the \(i\)th observation point, \(i = 1, \ldots, n\), \(n\) is the number of surrounding stations from which the interpolation is computed, \(\lambda_1, \ldots, \lambda_n\) are the weights assumed at the basis of variogram.

4. Results

4.1. Indexes caused cucumber low temperature disaster

Table 4(a) gives the greenhouse inside disaster indexes caused cucumber low temperature disaster for different development phases and Table 4(b–d) give the low temperature disaster indexes outside different three typical greenhouses for different development phases. What should be explained is that most solar greenhouses in Tianjin are not covered with film until October 20th, consequently, it is regarded that the greenhouse inside and outside air temperatures during the cucumber seeding phase are the same, namely, the greenhouse inside and outside disaster indexes of cucumber low temperature disaster during the seeding phases are the same, also the low temperature disaster indexes for three typical solar greenhouses during cucumber seeding phase are the same.

According to Table 4(b–d), we can see that there are different grades of cucumber low temperature disaster during three development phases in traditional Second generation greenhouse; there are low temperature disaster during cucumber seeding phase and fruiting phase in new type greenhouse, and lower greenhouse outside air temperature during fruiting phase can be undertaken compared with traditional Second generation greenhouse (because the heat retaining capability of new type greenhouse is better than that of traditional Second generation greenhouse); the
cucumber low temperature disaster in traditional cob wall greenhouse just happens during seeding phase, and there is no low temperature disaster during flowering phase and fruiting phase (because the traditional cob wall greenhouse has better heat retaining ability than other two typical greenhouses).

### 4.2. Disaster intensity spatial distribution of cucumber low temperature disaster

Computed the average value of cucumber low temperature disaster intensity index of 10 overwintering periods of 13 meteorological observation station in Tianjin, and in virtue of the spatial interpolation function of ArcGIS software (the OK interpolation method is adopted in this research) to obtain the low temperature disaster intensity spatial distribution result of cucumber for different development phases (Figure 2). What should be illustrated is that because of the same low temperature disaster indexes (including inside and outside indexes) during seeding phase for three typical greenhouses, the intensity spatial distribution result of different disaster grades for three typical greenhouses during seeding phase are the same, consequently, this study only takes the intensity spatial distribution result of cucumber low temperature disaster happened in the traditional Second generation greenhouse during seeding phase as an example. Besides, there is no low temperature disaster of cucumber during flowering phase and fruiting phase in the new type greenhouse, and there is no low temperature disaster during cucumber flowering phase and fruiting phase in the traditional cob wall greenhouse, therefore, as for the two types of greenhouses, this article only gives the intensity spatial distribution result of low temperature disaster for cucumber fruiting phase of new type greenhouse.

### Table 4(b). Greenhouse outside disaster indexes caused cucumber low temperature disaster of traditional second generation greenhouse.

| Development phase | Seeding phase (duration) | Flowering phase (duration) | Fruiting phase (duration) |
|-------------------|--------------------------|-----------------------------|--------------------------|
| Mild              | 11 °C ≤ T < 15 °C (72 h) | 9.2 °C ≤ T < 12.6 °C (72 h) | 0.4 °C ≤ T < 4.4 °C (72 h) |
| Moderate          | 8 °C ≤ T < 11 °C (48 h)  | 5 °C ≤ T < 9.2 °C (48 h)    | -3.1 °C ≤ T < 0.4 °C (48 h) |
| Severe            | T < 8 °C (24 h)          | T < 5 °C (24 h)             | T < -3.1 °C (24 h)        |

### Table 4(c). Greenhouse outside disaster indexes caused cucumber low temperature disaster of new type greenhouse.

| Development phase | Seeding phase (duration) | Flowering phase (duration) | Fruiting phase (duration) |
|-------------------|--------------------------|-----------------------------|--------------------------|
| Mild              | 11 °C ≤ T < 15 °C (72 h) |                            | -2.8 °C ≤ T < 1.6 °C (72 h) |
| Moderate          | 8 °C ≤ T < 11 °C (48 h)  |                            | -3.4 °C ≤ T < -2.8 °C (48 h) |
| Severe            | T < 8 °C (24 h)          |                            | T < -3.4 °C (24 h)        |

### Table 4(d). Greenhouse outside disaster indexes caused cucumber low temperature disaster of traditional cob wall greenhouse.

| Development phase | Seeding phase (duration) | Flowering phase (duration) | Fruiting phase (duration) |
|-------------------|--------------------------|-----------------------------|--------------------------|
| Mild              | 11 °C ≤ T < 15 °C (72 h) |                            |                          |
| Moderate          | 8 °C ≤ T < 11 °C (48 h)  |                            |                          |
| Severe            | T < 8 °C (24 h)          |                            |                          |
Figure 2. Low temperature disaster intensity index spatial distribution result of cucumber for different development phases and different types of greenhouses. *TS represents traditional second generation solar greenhouse; NT represents new type solar greenhouse; CP is short for comprehensive; CP-intensity represents comprehensive intensity index; Seed, flower and fruit represent different development phase of solar greenhouse cucumbers, respectively; Mild, moderate and severe represent different severity of low temperature disaster of solar greenhouse cucumbers.
According to Figure 2, we can see that the disaster intensity spatial distribution results of cucumber low temperature disaster for different types of solar greenhouses, different development phases and different disaster grades are different in Tianjin. As for the traditional Second generation greenhouses: during seeding phase, the high disaster intensity area of mild low temperature disaster is located in Ji County; and the high disaster intensity area of severe low temperature disaster is located in northwest Tianjin.

Figure 2. Continued.

According to Figure 2, we can see that the disaster intensity spatial distribution results of cucumber low temperature disaster for different types of solar greenhouses, different development phases and different disaster grades are different in Tianjin. As for the traditional Second generation greenhouses: during seeding phase, the high disaster intensity area of mild low temperature disaster is located in Ji County; and the high disaster intensity area of severe low temperature disaster is located in northwest Tianjin.
part of Baodi and the southwest edge of Ji County; and the low disaster intensity area of three-grade low temperature disaster during seeding phase is located in urban areas and Binhai New District, and the mild low temperature disaster intensity during seeding phase is obviously higher than that of the moderate and severe low temperature disaster. The above disaster intensity spatial distribution result of low temperature disaster of cucumber during seeding phase is also applicable to new type greenhouse and traditional cob wall greenhouse. During flowering phase, the high disaster intensity area of mild low temperature disaster is located in middle part of Binhai New District; and the high intensity area of moderate low temperature disaster is located in northwest part of Baodi and Ji County; and the high disaster intensity area of severe low temperature disaster is located in northwest part of Baodi district and the southwest edge of Ji County, and the mild low temperature disaster intensity during flowering phase is obviously higher than that of moderate and severe low temperature disaster. During fruiting phase, the high disaster intensity area of mild low temperature disaster is located in urban areas and middle part of Binhai New District; and the high disaster intensity area of moderate low temperature disaster is located in Dongli District and middle part of Binhai New District; and the high disaster intensity area of severe low temperature disaster is located in northwest part of Baodi district and the southwest edge of Ji County, and the disaster intensity of severe low temperature disaster during fruiting phase is obviously higher than that of mild and moderate disasters. Making a general survey of the whole development phase of greenhouse cucumber, the severe low temperature disaster intensity in fruiting phase is the highest in Tianjin, with the highest intensity index value of 0.392 m²K/W, and also the fruiting phase is the key phase which has direct influence on the final production and economic income of cucumber; the mild low temperature disaster intensity index during seeding phase, flowering phase and fruiting phase of cucumber are relatively higher, and the severe low temperature disaster intensity index during seeding phase is the lowest. As for the new type greenhouse, the low temperature disaster intensity during seeding phase is the same as that of the traditional Second generation greenhouse; there is no low temperature disaster during flowering phase; the high intensity area of mild low temperature disaster during fruiting phase is located in urban areas, Dongli District and the middle part of Binhai New District; there is only slight difference of moderate low temperature disaster intensity with generally low probability value as well; and the high disaster intensity area of severe low temperature disaster is located in northwest part of Baodi and southwest edge of Ji County. In addition, the moderate and severe disaster intensity index of cucumber during fruiting phase in traditional Second generation greenhouse are higher than that of new type greenhouse, and this is because that the latter one has better heat retaining performance than the former. Besides, the northwest part of Baodi and the southwest edge of Ji County will generally become high disaster intensity areas under different disaster grades during different development phases which related to the geographical positions: this area is in low terrain and is located in the flat area under north mountainous region, and the south part of Baodi has a high altitude, also there is funnelling effect caused by the northwest wind in winter, as a result, the temperature is low in this area.
4.3. Disaster losses spatial distribution of cucumber low temperature disaster

Cucumber yield reduction as a result of low temperature disaster is used to represent cucumber disaster losses in this study. Yield is mainly formed in the cucumber fruiting phase, consequently, it is evaluated the disaster losses happened in cucumber

Figure 3. Low temperature disaster losses spatial distribution result of cucumber during fruit phase of traditional second generation greenhouse (a–d) and new type greenhouse (e–h). *The meanings of TS, NT and CP refer to Figure 2; CP-losses represents comprehensive losses index.
fruiting phase. As the result shown in Section 4.1, there is no low temperature disaster during flowing phase and fruiting phase in the traditional cob wall greenhouse, consequently, it was only evaluated the disaster losses formed in the traditional second generation greenhouse and new type greenhouse.

Low temperature disaster losses spatial distribution result of cucumber is shown in Figure 3 (a–d for traditional second generation greenhouse and e–h for new type greenhouse). The following conclusions can be drawn: 1) The spatial distribution of...
losses index for two types of greenhouses are similar to the spatial distribution of intensity index; 2) the cucumber disaster losses index of the traditional second generation greenhouse is higher than that of the new type greenhouse for each disaster grade, because the heat retaining capacity of traditional second generation greenhouse

Figure 4. Comprehensive risk distribution of cucumber low temperature disaster of traditional second generation greenhouse (a), new type greenhouse (b) and the disaster risk zone for them (c for traditional second generation greenhouse and d for new type greenhouse). *The meanings of TS, NT and CP refer to Figure 2; CP-risk represents comprehensive disaster risk index.
is weaker than that of the new type greenhouse (the index of disaster resistance \( R \) is 0.0369 and 0.0932 for the traditional second generation greenhouse and the new type greenhouse, respectively, see Section 3.5); 3) For the two types of solar greenhouses, the areas with higher losses index located in Ji county, Baodi, Ninghe and Beicheng district for moderate, severe and comprehensive low temperature disaster; excluded the mild disaster with the higher index located in urban, Xiqing, Dongli and Binhai district.

### 4.4. Comprehensive risk distribution of cucumber low temperature disaster

To compare the low temperature disaster risk for two types of solar greenhouses, the same legend was assigned to the comprehensive risk distribution diagram of cucumber low temperature disaster for two types of solar greenhouses (Figure 4(a,b)). The low temperature disaster risk index of traditional second generation greenhouse ranges from 0.62 to 0.91, however, the risk index of the new type greenhouse just ranges from 0.08 to 0.158, which shows obviously the low temperature disaster risk of traditional second generation greenhouse is higher than that of the new type greenhouse. According to facility agriculture productive practice for many years, the risk index was classified for different disaster grade: risk index between 0 and 0.3 for mild disaster; risk index between 0.3 and 0.8 for moderate disaster; risk index between 0.8 and 1 for severe disaster. Consequently, the cucumbers grown in the new type greenhouse just suffered the mild low temperature risk during the overwintering period, which the comprehensive risk index just ranges from 0.083 to 0.158; to the contrary, the cucumbers grown in the traditional second generation greenhouse may suffer the moderate and severe disaster risk for different areas in Tianjin, which the comprehensive risk index just ranges from 0.616 to 0.910 (Figure 4(c,d)). For the traditional second generation greenhouse (Figure 4(c)), the deep red zone is high risk zone of cucumber low temperature disaster and the light red zone is medium risk zone of that. The deep red zone is always with the lower temperature area than other areas in Tianjin. Consequently, the new type greenhouse is more suitable for planting cucumber than the traditional second generation greenhouse during the overwintering period, otherwise, it is not recommended to plant cucumber in deep red area in the traditional second generation greenhouse because of higher disaster risk.

### 5. Discussion and conclusion

There are both ‘generality’ and ‘characters’ between the researches on meteorological disaster risk evaluation of facility crops with that of field crops. 1) The growth and development of facility crop is directly influenced by the microclimate in greenhouse, and indirectly influenced by the meteorological conditions out of the greenhouse; besides, there is great correlation between the greenhouse inside and outside meteorological conditions, therefore, it is the important basis to consider the correlation and the influence of both greenhouse inside and outside meteorological conditions on the growth and development of greenhouse crop for greenhouse crop meteorological disaster risk evaluation. 2) Meteorological disaster has different influences on the
greenhouse crop in different development phases, as well as the disaster performance and disaster loss; therefore, it is necessary to conduct risk evaluations of greenhouse crop for different development phases. 3) The different factors of greenhouse, such as structure, material and geographical position, lead to different heat-retaining capabilities of greenhouses, and the same outside disaster weather condition may lead to different influence on greenhouse crops in different greenhouses; therefore, it is necessary to conduct disaster risk evaluation aiming at different greenhouse types.

Taking the cucumber low temperature disaster indexes of greenhouse inside as the starting point, this research calculated the greenhouse outside disaster indexes caused low temperature disaster with the assurance rate algorithm; it first calculated the disaster intensity index of low temperature disaster of greenhouse cucumber for different disaster grades during different development phases; then the index of disaster resistant capability of solar greenhouse (R) was computed with the consideration of heat retaining capacity of solar greenhouse; third, the yield losses index was computed and caused by the low temperature disaster during fruiting phase; lastly, the comprehensive risk index was computed based on natural disaster risk evaluation theory for different types of greenhouse. Consequently, the comprehensive risk distribution diagram was conducted according to the comprehensive risk evaluation result. The cucumbers are grown in the new type greenhouse just suffered the mild low temperature risk during the overwintering period, which the comprehensive risk index just ranges from 0.083 to 0.158; the contrary, the cucumbers are grown in the traditional second generation greenhouse may suffer the moderate and severe disaster risk for different areas in Tianjin, which the comprehensive risk index just ranges from 0.616 to 0.910. The new type greenhouse is more suitable for planting cucumber than the traditional second generation greenhouse during overwintering period, otherwise, it is not recommended to plant cucumber in high risk zone in the traditional second generation greenhouse.

Compared with the existing researches (Wei and Zhao 2005; Cai et al. 2011; Huang et al. 2012; Yang et al. 2012; Yu 2012; Li et al. 2013), these researches layed emphasis on the influence of low temperature disaster on cucumber during different development phases and in different types of greenhouse. Besides, temperature is the main factor for greenhouse cucumber low temperature disaster, but because of the particularity of facility, the cucumber low temperature disaster is related to sunshine duration to some extent, which is not taken into consideration in this article, but will be supplemented in the future work.

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