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A Comparison of Methods for Investigating the Quantitative Relationships Between *Empoasca onukii* Matsuda (Hemiptera: Cicadellidae) and its Natural Enemies

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ABSTRACT

To systematically study the quantitative relationship between natural enemies and pests, this paper used grey relational analysis method, angular cosine coefficient method, fuzzy similarity priority ratio method and correlation coefficient method to analyze the closeness of the quantitative relationship between natural enemies and *Empoasca onukii* Matsuda in “Anjibaicha”, “Huangshandayezhong” and “Longjing 43” tea plantations. The conclusions obtained by the grey relational analysis method were used as a criterion to compare the sum of the rankings of the top three natural enemies, *Plexippus paykulli*, *Tetragnatha squamata* and *Ebrechtella tricuspidata*, thus comparing and discussing the similarities and differences between the conclusions obtained by the four research methods. The angular cosine coefficient method and grey relational analysis method yielded no major differences in conclusions, followed by the correlation coefficient method, with the fuzzy similarity priority ratio method yielding more varied results. According to the ranking analysis of the close relationship between the number of *E. onukii* and its natural enemies, *Tetragnatha squamata*, *Hylyphantes graminicola* and *Ebrechtella tricuspidata* are the first three natural enemies closely related to the number of *E. onukii*. This paper is an attempt to compare the consistency of research results of various research methods, which provides a reference for selecting research methods in analyzing the quantitative relationship between natural enemies and pests.

Keywords: Tea plantation, Natural enemies, *Empoasca onukii*, Quantitative relationship, Research method.

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INTRODUCTION

With the widespread consumption of tea as a beverage, the economic benefits of tea trees are gradually coming to the fore and the conservation of tea plantation ecosystems is being emphasized, while the yield and quality of tea are affected by many aspects, an important one being the direct harmful effects of pests (Yao, Li, & Xie, 2020; Wu, Tian, & Chen, 2020). The study of the relationship between pest and natural enemy populations is useful for analysing the behavioural habits and predation preferences of individuals in a population at a particular time (e.g. peak season), and is also important for evaluating the effects of various factors (e.g. the environment) on individuals or populations of pests and natural enemies. The study of the dynamics of the larger pattern as a whole is extremely useful in analysing the associations between different species and the extent and patterns of their adaptive capacity to external uncontrollable factors. The quantitative relationship between natural enemies and target pests in tea plantations is related to many factors, one of these factors is the magnitude of the predatory (or parasitic) effect of natural enemies on the target pest (Liu, Zhang, Bi, Yu, & Li, 2019). In recent years, Bi, Zou, Chen, Meng, & Wang (2000) studied several natural enemies closely related to *Aphis gossypii* (Glover) using the grey system analysis method. Cheng et al. (2018) analyzed several natural enemies closely related to *Frankliniella intonsa* (Trybom) and *Brevipalpus obovatus* (Donnadieu) using the method of geostatistics and grey relational analysis. Lin et al (2013) studied the relationship between planthoppers and natural enemies by grey system analysis. The degree of spatial aggregation of *Lygus lucorum* (Meyer-Dür) and its natural enemies was studied by Zhou et al (2019a) using blocked quadrat variance analysis and grey relational analysis. Gong et al (2019) studied the natural enemies most closely related to *E. onukii* in plum gardens based on the fuzzy similarity priority ratio method. They used fuzzy similarity priority ratio method, correlation coefficient method, angular cosine coefficient method and grey system analysis method to analyze the quantitative relationships between natural enemies and various pests, and their results are helpful for the conservation and utilization of natural enemies in pest control. Few studies have been conducted on the quantitative relationship between the same pest and its natural enemies using multiple methods. *E. onukii* is one of the main pests in tea plantations, and *Clubiona japonicola* Boes. et Str, *Oxyopes sertatus* L. Koch and *Tetragnatha squamata* Karsch are the first three natural enemies that are most closely related spatially to *E. onukii* (Sun et al, 2021). In this paper, we studied the quantitative relationships between *E. onukii* and its natural enemies in “Anjibaicha”, “Huangshandayezhong” and “Longjing 43” tea plantations. The results of the four methods, namely, grey relational analysis method, angular cosine coefficient method, fuzzy similarity priority ratio method and correlation coefficient method, were analyzed and compared to provide reference for the selection of research methods for the relationship between natural enemies and pest populations.

MATERIALS AND METHODS

Field investigation

A total of three tea plantations were surveyed in the Science and Technology Demonstration Park of Anhui Agricultural University (31°56′N, 117°12′E). The tea tree varieties in these three tea plantations are “Anjibaicha”, “Huangshandayezhong” and “Longjing 43”, with a total area of 0.2 hm^2. The survey period was from May 23, 2021 to September 17, 2021. The frequency of survey was about once every 10 days, 8 times in total. The three tea plantations were not connected to each other and were managed according to conventional measures. No chemical pesticides, ploughing and hoeing to loosen the soil before spring, appropriate irrigation in the morning and evening in summer according to weather conditions, light pruning after the end of autumn tea or before the sprouting of spring tea, clearing the garden in winter, cutting out diseased and weak branches, sweeping up dead branches and leaves on the ground and removing weeds from the tea garden.

According to the parallel jumping method, three rows were randomly selected in the tea garden, and a 2 m long sample square was taken at a distance of 1 m from each row of tea trees, with each sample square having an area of 2 m^2. 10 sample squares were selected for each row, and a total of 30 sample squares were taken. A visual survey was carried out by taking 10 leaves at random from each sample plot and observing the species of pests and natural enemies that adhered firmly to the tea trees. A solution of 1000 times laundry detergent was sprayed onto an enamel tray (40 cm long and 30 cm wide), and the branches of the tea trees in the sample plots were tapped to make the insects fall off and adhere to the tray. The species and number of pests and natural enemies in the tray were counted visually and recorded. Carry charts of common pest and spider species in tea plantations and compare them meticulously with the bugs in the tray for species identification in terms of shape, colour, size, etc. Some species that could not be identified were numbered, stored in special bottles and brought back to the laboratory for observation and identification.

Analysis methods

Grey relational analysis method

$$\xi_{ij} = \frac{\min\min|Y_i(k)-X_j(k)| + \rho\max\max|Y_i(k)-X_j(k)|}{|Y_i(k)-X_j(k)| + \rho\max\max|Y_i(k)-X_j(k)|}$$

The above equation ρ is the resolution coefficient, it’s usually between 0 and 1, this paper takes $\rho = 0.8$. $\min\min|Y_i(k)-X_j(k)|$ is the 2-level minimum difference, and $\max\max|Y_i(k)-X_j(k)|$ is the maximum difference of 2 levels (Deng, 1990).

From the above equation, the grey relational coefficient between the number of natural enemies and pest is $R(Y_i, X_j) = \frac{1}{n}\sum r_{ij}(k)$. The higher the grey relational

coefficient between natural enemies and pest populations, the closer the relationship between natural enemies and pest populations (Legendre & Fortin, 1989).

Angular cosine coefficient method

The angular cosine coefficients between the number of pest and its natural enemies were analyzed using the angular cosine coefficient method (Xu, 2002). The higher the value of the angular cosine coefficient, the closer the relationship between the numbers of the two species. The formula for the angular cosine coefficient is

$$\alpha_{ij} = \frac{\sum_{k=1}^{n} x_{ik} \cdot x_{jk}}{[(\sum_{k=1}^{n} x_{ik}^2) \cdot (\sum_{k=1}^{n} x_{jk}^2)]^{1/2}}$$

where x_{ik} and x_{jk} are the number of individuals of species i and j at the k_{th} sample.

Fuzzy similarity priority ratio method

The similarity priority ratio is a way to perform a metric in which a pair of samples is analyzed with a fixed sample, so that the one between the two that is more similar to the fixed sample is discussed (Lu, Yu, & Li, 2006; Zhao & Yang, 2005). If the paired samples are samples M_i and M_j, respectively, and the fixed sample is M_k, then the fuzzy similarity priority ratio Z_{ij} is

(1) If Z_{ij} is between [0, 0.5], it means that M_j has priority over M_i;

(2) If Z_{ij} is between [0.5, 1.0], it means that M_i has priority over M_j;

(3) If $Z_{ij} = 1$, then M_i has priority over M_j; if $Z_{ij} = 0$, then M_j has priority over M_i; if $Z_{ij} = 0.5$, then M_i and M_j do not have much difference in priority.

Comparisons between samples M_i and samples M_j and fixed samples M_k are mostly made using the Hemming distance $\beta_{ij} = \frac{d_{ki}}{d_{ki} + d_{kj}}$. The fuzzy similarity priority ratio analysis in this paper is performed by the DPS software.

Correlation coefficient method

The correlation coefficient is a quantity used to analyze the degree of linear correlation between two or more variables and can be expressed by r. There are various ways to define it, and different ways can be chosen according to different research objects, the most common one is Pearson correlation coefficient.

The definition formula is

$$r(X,Y) = \frac{\mathrm{Cov}(X,Y)}{\sqrt{\mathrm{Var}[X]\mathrm{Var}[Y]}}$$

Where $\mathrm{Cov}(X,Y) = \sum (X - \bar{X})(Y - \bar{Y})$ is the covariance of X and Y, $\mathrm{Var}[X] = \sum (X - \bar{X})^2$

is the variance of X and $\mathrm{Var}[Y]=\sum(Y-\overline{Y})^2$ is the variance of Y. The absolute value of the r value is between 0 and 1. Usually, the closer r is to 1, the stronger the correlation between the two quantities X and Y. Conversely, the closer r is to 0, the weaker the correlation between the two quantities X and Y.

RESULTS

The top 11 natural enemies in the tea plantations of “Anjibaicha”, “Huangshandayezhong” and “Longjing 43” were *Tetragnatha squamata*, *Tetragnatha maxillosa*, *Hylyphantes graminicola, Xysticus ephippiatus, Ebrechtella tricuspidata, Theridion octomaculatum, Clubiona japonicola, Clubiona reichlini, Oxyopes sertatus, Plexippus paykulli* and *Plexippus setipes*. Therefore, these 11 species were selected as the main natural enemies to study their close relationship with *E. onukii*, and their population dynamics are listed in Table 1.

Table 1. Population dynamics of *E. onukii* and its natural enemies in the three tea plantations (individual/30 quadrats).

Tea plantation	Date	Population[1]											
		Y	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Anjibaicha	5-23	69	3	4	15	2	13	0	1	0	0	7	2
	6-4	166	2	13	0	5	2	0	0	0	0	4	0
	6-20	134	8	9	0	7	1	1	5	3	3	2	0
	7-8	441	65	4	46	13	34	60	29	132	42	32	0
	8-10	246	27	13	19	36	7	34	24	102	19	32	42
	8-22	245	20	3	26	27	17	12	30	89	45	22	13
	9-6	193	20	8	21	38	19	28	11	38	56	19	22
	9-17	30	9	5	10	7	11	11	15	4	12	12	10
Huangshan dayezhong	5-23	106	8	1	14	3	8	3	3	0	2	4	1
	6-4	513	14	12	3	10	14	12	5	7	1	13	0
	6-20	507	10	4	7	2	8	6	32	18	2	17	0
	7-8	371	19	24	33	56	30	26	10	23	26	29	0
	8-10	755	31	25	28	29	23	30	20	65	22	30	26
	8-22	348	34	10	44	19	17	37	31	57	22	24	17
	9-6	264	35	0	28	18	10	21	24	28	30	13	39
	9-17	28	8	0	10	9	9	17	20	7	37	6	15
Longjing 43	5-23	267	9	1	4	2	7	0	2	0	0	5	0
	6-4	576	4	0	1	7	5	3	2	2	0	0	5
	6-20	641	2	1	8	7	5	0	2	12	2	7	0
	7-8	866	30	8	46	49	22	21	11	38	30	37	0
	8-10	679	27	8	25	18	17	36	14	36	37	27	24
	8-22	543	34	12	31	23	12	33	35	27	51	28	2
	9-6	270	16	0	13	21	10	15	16	14	128	22	13
	9-17	15	12	0	15	6	5	15	10	14	23	7	14

[1]Y: *Empoasca onukii*; X_1: *Tetragnatha squamata*; X_2: *Tetragnatha maxillosa*; X_3: *Hylyphantes graminicola*; X_4: *Xysticus ephippiatus*; X_5: *Ebrechtella tricuspidata*; X_6: *Theridion octomaculatum*; X_7: *Clubiona japonicola*; X_8: *Clubiona reichlini*; X_9: *Oxyopes sertatus*; X_{10}: *Plexippus paykulli*; X_{11}: *Plexippus setipes* (The same below)

Results of the grey relational analysis method

The grey relational coefficients between the number of *E. onukii* and its natural enemies obtained by grey relational analysis method are listed in Table 2. The top three natural enemies that were closely related to the population of *E. onukii* were *Tetragnatha squamata* (X_1, 0.855), *Plexippus paykulli* (X_{10}, 0.846) and *Hylyphantes graminicola* (X_3, 0.826) in "Anjibaicha" tea plantation; *Plexippus paykulli* (X_{10}, 0.853), *Ebrechtella tricuspidata* (X_5, 0.814) and *Tetragnatha maxillosa* (X_2, 0.813) in "Huangshandayezhong" tea plantation; and *Ebrechtella tricuspidata* (X_5, 0.875), *Tetragnatha squamata* (X_1, 0.841) and *Hylyphantes graminicola* (X_3, 0.825) in "Longjing 43" tea plantation. Based on the sum of the grey relational coefficient of the same natural enemy in the three tea plantations, the top three natural enemies that were closely related to the population of *E. onukii* were *Plexippus paykulli* (X_{10}, 2.521), *Tetragnatha squamata* (X_1, 2.490) and *Ebrechtella tricuspidata* (X_5, 2.488).

Table 2. Grey relational coefficient and serial number between *E. onukii* and its natural enemies in the three tea plantations.

Tea plantation	Project[1]	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Anjibaicha	A	0.855	0.774	0.826	0.771	0.799	0.764	0.802	0.799	0.762	0.846	0.700
	B	1	7	3	8	6	9	4	5	10	2	11
Huangshan dayezhong	A	0.795	0.813	0.728	0.774	0.814	0.769	0.754	0.794	0.708	0.853	0.700
	B	4	3	9	6	2	7	8	5	10	1	11
Longjing 43	A	0.841	0.790	0.825	0.816	0.875	0.763	0.756	0.823	0.740	0.822	0.686
	B	2	7	3	6	1	8	9	4	10	5	11
Total grey relational coefficient		2.490	2.376	2.378	2.361	2.488	2.296	2.312	2.417	2.211	2.521	2.086
Total serial number		2	6	5	7	3	9	8	4	10	1	11

[1]A: Grey relational coefficient; B: Serial number of the grey relational coefficient

Results of the angular cosine coefficient method

The angular cosine coefficients between the number of target pest and its natural enemies and their serial numbers are listed in Table 3. In 2021, the top three natural enemies closely related to the population of *E. onukii* were *Tetragnatha squamata* (X_1, 0.941), *Plexippus paykulli* (X_{10}, 0.927), and *Hylyphantes graminicola* (X_3, 0.923) in "Anjibaicha" tea plantation; *Plexippus paykulli* (X_{10}, 0.933), *Ebrechtella tricuspidata* (X_5, 0.876) and *Tetragnatha maxillosa* (X_2, 0.865) in "Huangshandayezhong" tea plantation; *Ebrechtella tricuspidata* (X_5, 0.916), *Clubiona reichlini* (X_8, 0.866) and *Xysticus ephippiatus* (X_4, 0.856) in "Longjing 43" tea plantation. According to the total angular cosine coefficient, the top three natural enemies that were closely related to the population of *E. onukii* were *Plexippus paykulli* (X_{10}, 2.707), *Ebrechtella tricuspidata* (X_5, 2.682) and *Clubiona reichlini* (X_8, 2.640) in the combined analysis of the three tea plantations.

Table 3. The angular cosine coefficient and serial number between *E. onukii* and its natural enemies in the three tea plantations.

Tea plantation	Project[1]	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Anjibaicha	C	0.941	0.741	0.923	0.787	0.891	0.902	0.891	0.922	0.836	0.927	0.571
	D	1	10	3	9	7	5	6	4	8	2	11
Huangshan dayezhong	C	0.844	0.865	0.748	0.729	0.876	0.817	0.786	0.852	0.596	0.933	0.584
	D	5	3	8	9	2	6	7	4	10	1	11
Longjing 43	C	0.826	0.773	0.842	0.856	0.916	0.751	0.673	0.866	0.504	0.848	0.498
	D	6	7	5	3	1	8	9	2	10	4	11
Total angular cosine coefficient		2.611	2.379	2.513	2.371	2.682	2.469	2.350	2.640	1.935	2.707	1.652
Total serial number		4	7	5	8	2	6	9	3	10	1	11

[1]C: Angular cosine coefficient; D: Serial number of the angular cosine coefficient

Results of the fuzzy similarity priority ratio method

The similarities between the numbers of target pest and natural enemies in the three tea plantations and their serial numbers are listed in Table 4. The top three natural enemies closely related to the numbers of *E. onukii* were *Tetragnatha squamata* (X_1), *Hylyphantes graminicola* (X_3) and *Theridion octomaculatum* (X_6) in "Anjibaicha" tea plantation; *Clubiona reichlini* (X_8), *Xysticus ephippiatus* (X_4) and *Oxyopes sertatus* (X_9) in "Huangshandayezhong" tea plantation; *Tetragnatha squamata* (X_1), *Hylyphantes graminicola* (X_3) and *Oxyopes sertatus* (X_9) in "Longjing 43" tea plantation. A comprehensive analysis showed that the top three natural enemies that were closely related to the population of *E. onukii* were *Tetragnatha squamata* (X_1), *Clubiona reichlini* (X_8) and *Hylyphantes graminicola* (X_3).

Table 4. The similarity and serial number between *E. onukii* and its natural enemies in the three tea plantations.

Tea plantation	Project[1]	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Anjibaicha	E	30	60	32	43	43	34	41	35	48	38	55
	F	1	11	2	7	8	3	6	4	9	5	10
Huangsha dayezhong	E	37	52	40	35	47	43	43	31	36	39	49
	F	4	11	6	2	9	7	8	1	3	5	10
Longjing 43	E	27	63	31	33	45	37	41	33	32	33	50
	F	1	11	2	6	9	7	8	4	3	5	10
Total similarity		94	175	103	111	135	114	125	99	116	110	154
Total serial number		1	11	3	5	9	6	8	2	7	4	10

[1]E: Similarity; F: Serial number of the similarity

Results of the correlation coefficient method

The correlation coefficients between the numbers of *E. onukii* and its natural enemies in the three tea plantations and their serial numbers are listed in Table 5. The top three natural enemies that were closely related to the number of *E. onukii* were *Tetragnatha squamata* (X_1, 0.910), *Clubiona reichlini* (X_8, 0.895) and *Theridion*

octomaculatum (X_6, 0.839) in "Anjibaicha" tea plantation; *Plexippus setipes* (X_{11}, 0.734), *Tetragnatha maxillosa* (X_2, 0.715) and *Clubiona reichlini* (X_8, 0.606) in the tea plantation of "Huangshandayezhong"; *Ebrechtella tricuspidata* (X_5, 0.640), *Xysticus ephippiatus* (X_4, 0.606) and *Tetragnatha maxillosa* (X_2, 0.573) in "Longjing 43" tea plantation. According to the sum of the correlation coefficients of the same natural enemies in the three tea plantations, the top three natural enemies that were closely related to *E. onukii* were *Clubiona reichlini* (X_8, 2.072), *Ebrechtella tricuspidata* (X_5, 1.799), and *Tetragnatha squamata* (X_1, 1.659).

Table 5. Correlation coefficient and serial number between *E. onukii* and its natural enemies in the three tea plantations.

Tea Plantation	Project[1]	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Anjibaicha	G	0.910	0.058	0.796	0.381	0.677	0.839	0.688	0.895	0.605	0.759	0.095
	H	1	11	4	9	7	3	6	2	8	5	10
Huangshan dayezhong	G	0.382	0.715	0.108	0.274	0.482	0.297	0.174	0.606	0.290	0.290	0.734
	H	5	2	11	9	4	6	10	3	7	8	1
Longjing 43	G	0.367	0.573	0.517	0.606	0.640	0.266	0.053	0.571	0.191	0.510	0.233
	H	7	3	5	2	1	8	11	4	10	6	9
Total correlation coefficient		1.659	1.230	1.422	1.261	1.799	1.402	0.915	2.072	0.124	0.980	0.596
Total serial number		3	7	4	6	2	5	9	1	11	8	10

[1]G: Correlation coefficient; H: Serial number of correlation coefficient

Comparison of the results of the four methods

The results obtained from the four methods are listed in Table 6, and the differences in the results of the other three methods are compared using the results of the grey relational analysis method as a control.

Table 6. The results of the four methods.

Tea plantation	Method[1]	The top three natural enemies closely related to *E. onukii*		
		1	2	3
Anjibaicha	I	X_1	X_{10}	X_3
	J	X_1	X_{10}	X_3
	K	X_1	X_3	X_6
	L	X_1	X_8	X_6
Huangshandayezhong	I	X_{10}	X_5	X_2
	J	X_{10}	X_5	X_2
	K	X_8	X_4	X_9
	L	X_{11}	X_2	X_8
Longjing 43	I	X_5	X_1	X_3
	J	X_5	X_8	X_4
	K	X_1	X_3	X_9
	L	X_5	X_4	X_2

[1]I: Grey relational analysis method; J: Angular cosine coefficient method; K: Fuzzy similarity priority ratio method; L: Correlation coefficient method (The same below)

The differences between the results of the four methods were analysed and compared for the same tea plantation. Of the 11 natural enemies in "Anjibaicha" tea

plantation, the top three natural enemies that were closely related to the number of *E. onukii* were selected for comparison. The results of the grey relational analysis method were *Tetragnatha squamata* (X_1), *Plexippus paykulli* (X_{10}) and *Hylyphantes graminicola* (X_3), and the results of the angular cosine coefficient method were also in the order of these three species, which were identical to the top three natural enemies in the grey relational analysis method. The results of the fuzzy similarity priority ratio method were *Tetragnatha squamata* (X_1), *Hylyphantes graminicola* (X_3) and *Theridion octomaculatum* (X_6), with two species identical to the grey relational analysis method. The results of the correlation coefficient method were *Tetragnatha squamata* (X_1), *Clubiona reichlini* (X_8) and *Theridion octomaculatum* (X_6), with only one species identical to the grey relational analysis method. A comprehensive analysis shows that the results of the angular cosine coefficient method and the grey relational analysis method are the same for the top 3 natural enemies; the results of the fuzzy similarity priority ratio method differ more from the grey relational analysis method, and the results of the correlation coefficient method differ most from the grey relational analysis method.

In the same analysis, it can be concluded that in the tea plantation of "Huangshandayezhong", the top three natural enemies were the same in the angular cosine coefficient method and the grey relational analysis method; in the comparison between the results of the correlation coefficient method and the grey relational analysis method, only one of the top three natural enemies was the same, so it is more different from the results of the grey relational analysis method; while in the comparison between the results of the fuzzy similarity priority ratio method and the grey relational analysis method, the top three natural enemies are all different, so it is the most different from the results of the grey relational analysis method.

For "Longjing 43" tea plantation, the results of the angular cosine coefficient method, the fuzzy similarity priority ratio method and the correlation coefficient method were all the same for only one of the top three natural enemies compared to the results of the grey relational analysis method, and all differed significantly from the results of the grey relational analysis method.

A comprehensive analysis of the results of the relationship between the number of *E. onukii* and its natural enemies in the three tea plantations

To comprehensively analyze the differences of the results obtained by the four methods in the three tea plantations, the ranking of the natural enemies in relation to the number of *E. onukii* in the three tea plantations was analyzed and compared, and the results of the comprehensive analysis of Tables 2-5 are listed in Table 7. The results of the grey relational analysis method were used as the basis for comparison, and the results obtained by the four research methods were comprehensively analyzed according to the changes in the ranking of the natural enemies.

The sum of the top three natural enemies (*Plexippus paykulli*, *Tetragnatha squamata* and *Ebrechtella tricuspidata*) that were closely related to *E. onukii* by the

grey relational analysis method was used as the basis for comparison, and the greater the sum of the resulting rankings, the greater the variation from the results obtained by the grey relational analysis method. The sum of the rankings of the grey relational analysis method was 6, the angular cosine coefficient method was 7, the fuzzy similarity priority ratio method was 14, and the correlation coefficient method was 13. The comparison was then based on the sum of the rankings of the top 5 natural enemies of the grey relational analysis method, which was 15 for the grey relational analysis method, 15 for the angular cosine coefficient method, 19 for the fuzzy similarity priority ratio method, and 18 for the correlation coefficient method. The difference between the results obtained by the angular cosine coefficient analysis and the grey relational analysis method was small, followed by the correlation coefficient method, and the fuzzy similarity priority ratio method had a large difference in the results. The sum of the frequencies of the top three natural enemies obtained by the four methods in the three tea plantations was compared (up to 12 times), *Tetragnatha squamata* (X_1) for 6, *Hylyphantes graminicola* (X_3) for 5, *Ebrechtella tricuspidata* (X_5) for 5, *Tetragnatha maxillosa* (X_2) for 4, *Clubiona reichlini* (X_8) for 4, *Plexippus paykulli* (X_{10}) for 4, *Xysticus ephippiatus* (X_4) for 3, *Theridion octomaculatum* (X_6) for 2, *Oxyopes sertatus* (X_9) for 2, *Plexippus setipes* (X_{11}) for 1, *Clubiona japonicola* (X_7) for 0. Therefore, *Tetragnatha squamata* (X_1), *Hylyphantes graminicola* (X_3) and *Ebrechtella tricuspidata* (X_5) were the three natural enemies most closely related to the number of *E. onukii*.

Table 7. Comparison of the results of the four analysis methods.

Method	Total serial number of natural enemies in the three tea plantations											Remarks	
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	Sum of the serial numbers of X_{10}, X_1 and X_5	Sum of the serial numbers of X_{10}, X_1, X_5, X_8 and X_3
I	2	6	5	7	3	9	8	4	10	1	11	6	15
J	4	7	5	8	2	6	9	3	10	1	11	7	15
K	1	11	3	5	9	6	8	2	7	4	10	14	19
L	3	7	4	6	2	5	9	1	11	8	10	13	18

DISCUSSION

Generally, the higher the number of pests and the more adequate the sample, the more accurate the results obtained and the closer the relationship between the number of pests and natural enemies reflected in the real situation (Zou, 1997). The relationship between natural enemies and pests is an interdependent and mutually constraining relationship, which is expressed in the number of ups and downs, not a linear relationship, so the results of using the correlation coefficient method are not accurate enough. The fuzzy similarity priority ratio is a form of fuzzy metric, which is calculated to get the ordinal number of the sample, the smaller the ordinal number value of the sample, the more similar the sample is to the fixed sample. The degree of influence of each factor on the sample is different, so it is necessary to give certain weights to each factor, so that the results obtained will be more in line with the actual

situation. However, assigning weight is highly subjective and depends on professional knowledge. The angular cosine coefficient method solves the problem that the two are linearly related. Grey relational analysis method can solve the problem of both linear and non-linear relationship. Therefore, it is a more ideal analysis method, so this paper compares the similarities and differences of several analysis results based on the analysis results of grey relational analysis method. This paper can provide reference for similar analysis.

For the closeness of the quantitative relationship between natural enemies and target pest, in the case of tea plantations, the main factor is the magnitude of the predatory (or parasitic) effect of natural enemies on the target pest. Therefore, the study of the quantitative relationship between natural enemies and pest is of great importance and is one of the main research directions in insect ecology (Veres, Petit, Conord, & Lavigne, 2013). Zhou et al (2019b) analyzed and compared the dominant species of natural enemies of *Breuipalpus oboyats* Donnadieu in "Wuniuzao" and "Baihaozao" tea plantations by using the geostatistical method combined with the ecological niche method. Cheng et al (2022) used the geostatistical method and the angular cosine coefficient method to identify the natural enemy species which are close to Ricanidae in spatial relationship. Zhang et al (2021) studied the relationship between natural enemies and *Breuipalpus oboyats* Donnadieu in time and space by niche analysis and geostatistics combined with angular cosine coefficient method. Qian et al (2019) creatively combined the angular cosine coefficient with niche similarity coefficient and the range of spatial dependence of semivariogram theoretical model in geostatistics to analyze the relationship of neutral insects, mosquitoes and natural enemies. All the above studies involve the four methods mentioned in this paper to study the relationship between natural enemies and pests in tea plantations, which provide a scientific reference for effective pest control. In addition, the geostatistical method mentioned above is a method for studying the spatial relationship between pests and natural enemies, and can accurately reflect the spatial predation preferences of natural enemies on pests. The method is applicable to the analysis of spatial relationships between natural enemies and pests at the largest scale (or range) of tea plantations, tea farms and tea hills in any orientation, as well as to the study of spatial relationships between natural enemies and pests in homogeneous and non-homogeneous habitats, provided that the distances between sampling squares are equidistant. The ecological niche method reflects the temporal following relationship between pests and natural enemies, the greater the temporal ecological niche overlap index, the closer the natural enemies follow the pests in time. Combining these methods with the methods mentioned in this paper for studying quantitative relationships provides a more comprehensive assessment of the dominant species of natural enemies of pests from three aspects: spatial, temporal and quantitative. The four methods studied in this paper are important models that have been creatively proposed by many ecologists and mathematicians based on their own findings and the conclusions obtained by others, contributing to the development and progress of ecology.

CONCLUSIONS

The grey relational analysis method, angular cosine coefficient method, fuzzy similarity priority ratio method and correlation coefficient method were used to study the quantitative relationship between natural enemies and *E. onukii* in “Anjibaicha”, “Huangshandayezhong” and “Longjing 43” tea plantations. The results of the four methods were ranked in terms of the closeness of the relationship between natural enemies and *E. onukii*, and the top three natural enemies derived from the grey relational analysis method, *Plexippus paykulli* (X_{10}), *Tetragnatha squamata* (X_1), and *Ebrechtella tricuspidata* (X_5), were used as control specimens. The results of the angular cosine coefficient analysis method and the grey relational analysis method were less different, followed by the correlation coefficient method, and the results of the fuzzy similarity priority ratio method were more different. Based on the sum of the number of occurrences of natural enemies in the top three positions in the four methods, it was concluded that *Tetragnatha squamata*, *Hylyphantes graminicola* and *Ebrechtella tricuspidata* were the top three natural enemies that were closely related to the number of *E. onukii.*

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